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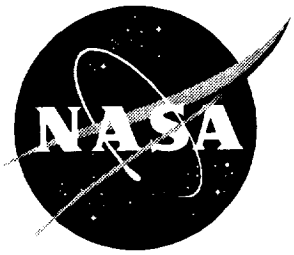

Computer Model To Simulate Testing at the National Transonic Facility

Raymond E. Mineck, Lewis R. Owens, Jr., Richard A. Wahls, and Judith A. Hannon

(NASA-TM-4664) COMPUTER MODEL TO SIMULATE TESTING AT THE NATIONAL TRANSONIC FACILITY (NASA. Langley Research Center) 45 p

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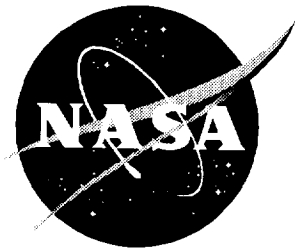
August 1995



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August 1995

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Abstract

A computer model has been developed to simulate the processes involved in the operation of the National Transonic Facility (NTF), a large cryogenic wind tunnel at the Langley Research Center. The simulation was verified by comparing the simulated results with previously acquired data from three experimental wind tunnel test programs in the NTF. The comparisons suggest that the computer model simulates reasonably well the processes that determine the liquid nitrogen (LN_2) consumption, electrical consumption, fan-on time, and the test time required to complete a test plan at the NTF. From these limited comparisons, it appears that the results from the simulation model are generally within about 10 percent of the actual NTF test results. The use of actual data acquisition times in the simulation produced better estimates of the LN_2 usage, as expected. Additional comparisons are needed to refine the model constants. The model will typically produce optimistic results since the times and rates included in the model are typically the optimum values. Any deviation from the optimum values will lead to longer times or increased LN_2 and electrical consumption for the proposed test plan. Computer code operating instructions and listings of sample input and output files have been included.

Introduction

Cryogenic wind tunnels are generally more expensive to operate than conventional wind tunnels that have similar test envelopes of Mach number and pressure. The cost of the liquid nitrogen (LN_2) can be a significant portion of the cost to operate a cryogenic wind tunnel. The amount of LN_2 required to conduct experiments will depend on the particular test conditions that are selected for the test.

A computer simulation model of the processes encountered in cryogenic wind tunnel testing has been developed. The model provides a consistent method for estimating the amount of time and consumables (LN_2, electricity, and high-pressure air) necessary to complete a proposed test plan. The techniques that were used to estimate the time and the consumables were based on the design and operational databases of the National Transonic Facility (NTF) at the Langley Research Center.

This report describes the various processes that are included in the computer simulation model. In order to assess the validity of the model, results from three wind tunnel tests are compared with results from the computer model. Instructions are provided to prepare the input files, to create the executable program module, and to run the computer model in appendix A. Additional appendixes describe the required program input files, the program output files, a set of input files, and the associated output file to serve as a sample case.

Symbols

a, b, c_1	parameters used in equations
c	dummy parameter
GN_2	gaseous nitrogen
LN_2	liquid nitrogen
T	test gas temperature, °F
$\dot{T}$	time rate change of test gas temperature, °F/hr
t	time, sec
$\dot{V}$	LN_2 pump rate, gal/min
Δ	change in parameter
τ	dummy parameter

Subscripts:

l	lower
m	value at lowest temperature for maximum cooldown rate
u	upper

Abbreviations:

AOA	angle of attack
ESP	electronically scanned pressures
NTF	National Transonic Facility

NTF Simulation Model Description

The NTF is a fan-driven, pressure tunnel which uses either air or gaseous nitrogen (GN_2) as a test gas. A sketch of the NTF is presented in figure 1. Electricity powers the motors that drive the fan. High-pressure air (about 350 psi) is used to pressurize the tunnel circuit for air operations and to provide purge air for the model access housings. Liquid nitrogen is vaporized to supply and cool the test gas for GN_2 operations. Operation of the NTF involves the consumption of electricity, high-pressure air, and LN_2.

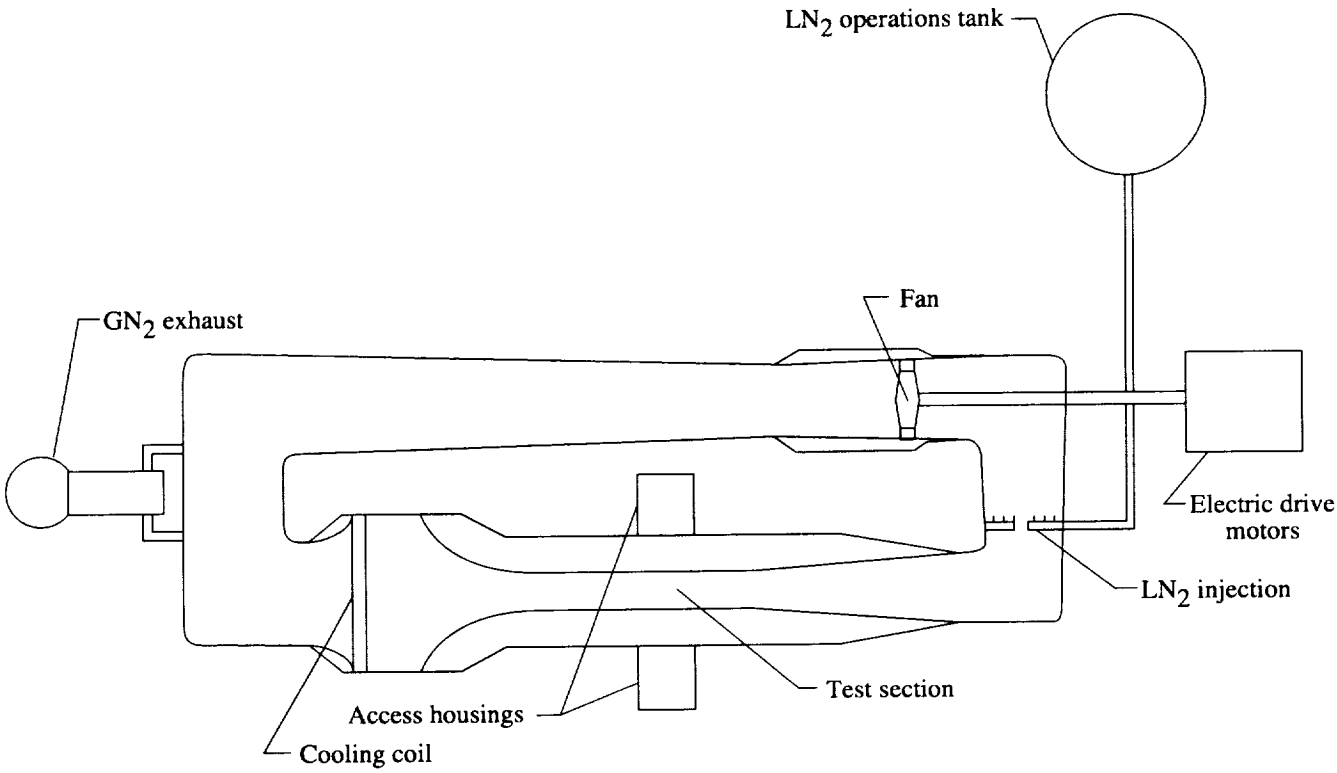


Figure 1. Schematic of NTF (not to scale).

The computer model described herein simulates the operation of the NTF in the GN_2 and the air operations modes by a series of simulated processes. A sketch of the data flow is presented in figure 2. The model requires four input files: simulation parameters, test conditions, angle-of-attack schedules, and the test plan. The model uses the first three files to form a database as it processes each item in the test plan and generates two output files, one a tabular listing of the results from the simulation and the other a file that can be used with a user supplied plotting program.

The model sequentially processes each item or commanded process in the test plan. The commanded processes include model installation, tunnel run, model change, holiday shutdown, tunnel downtime, and model removal. Some commanded processes initiate one or more automatic processes that are needed to complete the commanded process. In addition, the model includes algorithms to model the heat transfer from the tunnel shell, to model the LN_2 supply system, to model the elements involved in data acquisition, and to check for time or LN_2 supply constraint violations. This section describes the commanded processes, the automatic processes, and the support algorithms used by the model. In the description of each process, the parameters for the computer model that are used by each particular process are identified in parentheses by the word *parameter* followed by the parameter name in boldface type.

The time required to complete the process and the rates of consumption for LN_2, electricity, and high-pressure air are either defined for each process or computed from other input parameters. The LN_2, electricity, and high-pressure air consumed during the process are determined from the product of the consumption rate and the time required to complete the process. The model tracks the liquid level in up to three LN_2 tanks, the total consumption of LN_2, electricity, high-pressure air, and the number of occurrences and duration of each process. In addition, the model tracks the lost time because a process could not be completed before the end of the workday or because there was insufficient LN_2 to complete the process.

Commanded Processes

The test plan file consists of a sequence of commanded processes that are to be simulated by the computer model. The commanded processes are model installation, tunnel run, model change, model removal, holiday shutdown, and tunnel shutdown. Note that during all processes, LN_2 production and delivery are possible. However, production takes place only when there is space in the manufacturer's supply tank, and delivery

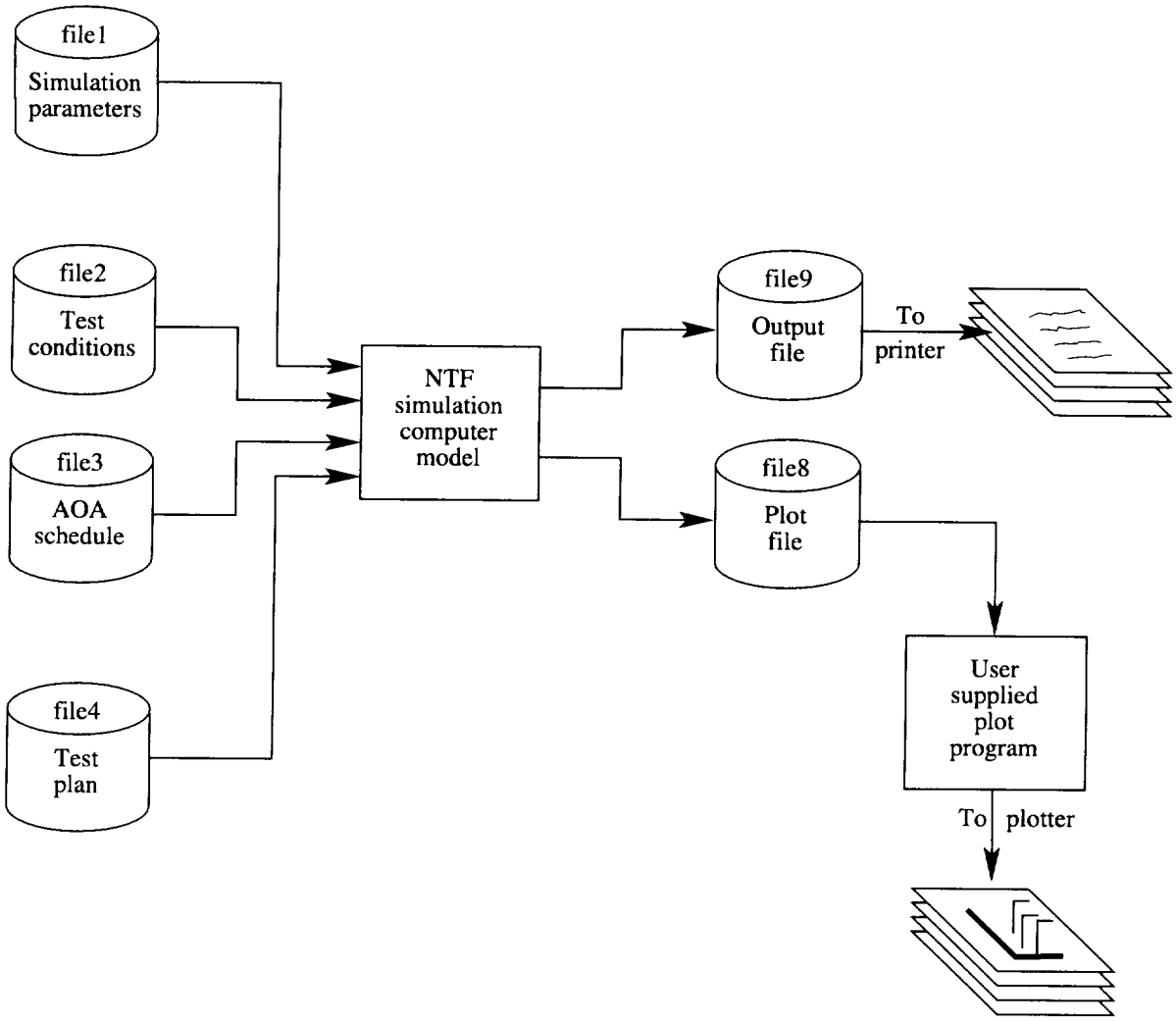


Figure 2. Sketch of data flow.

takes place only when there is space in the NTF operations tank or the optional storage tank.

Each process is subjected to constraints of time and LN_2 availability. Certain processes must be completed before the end of the workday, and there must be adequate LN_2, if required, to complete the process. If the time constraint is violated, the lost time is tracked, and a delay is inserted until the end of the current workday. If the available LN_2 (amount in the operations tank and available through delivery from the supply tank or transferred from the optional storage tank) is inadequate, a delay is inserted to fill the NTF operations tank to a fixed value in the source code (typically 95 percent or a filled tank). A filled tank is desirable to avoid a situation in which the model would repeatedly simulate a delay for a small LN_2 transfer that would be sufficient for a single polar followed by a single polar in the GN_2 mode. (In practice, the delay could be shorter if less than a full tank of LN_2 is needed to complete the polars in the current tunnel run.) Heat transfer from the tunnel shell and high-pressure-air use for the access housings are modeled during any delays for GN_2 operations. The commanded processes are described below.

Model Installation or Model Removal

The model installation and the model removal processes are simulated by a user specified block of time in hours. If the time to complete the process extends past the end of the workday, it is continued at the beginning of the next workday. A flowchart that shows the logic for model installation and model removal processes is presented in figure 3. Before beginning the model removal process, the test gas is warmed, and a gas exchange is completed if the current operations mode is set for GN_2 (cryogenic) testing. (See the "Warm-Up" and "Gas Exchange" sections.) Electricity, LN_2, and high-pressure air are not consumed during either the model installation or removal processes.

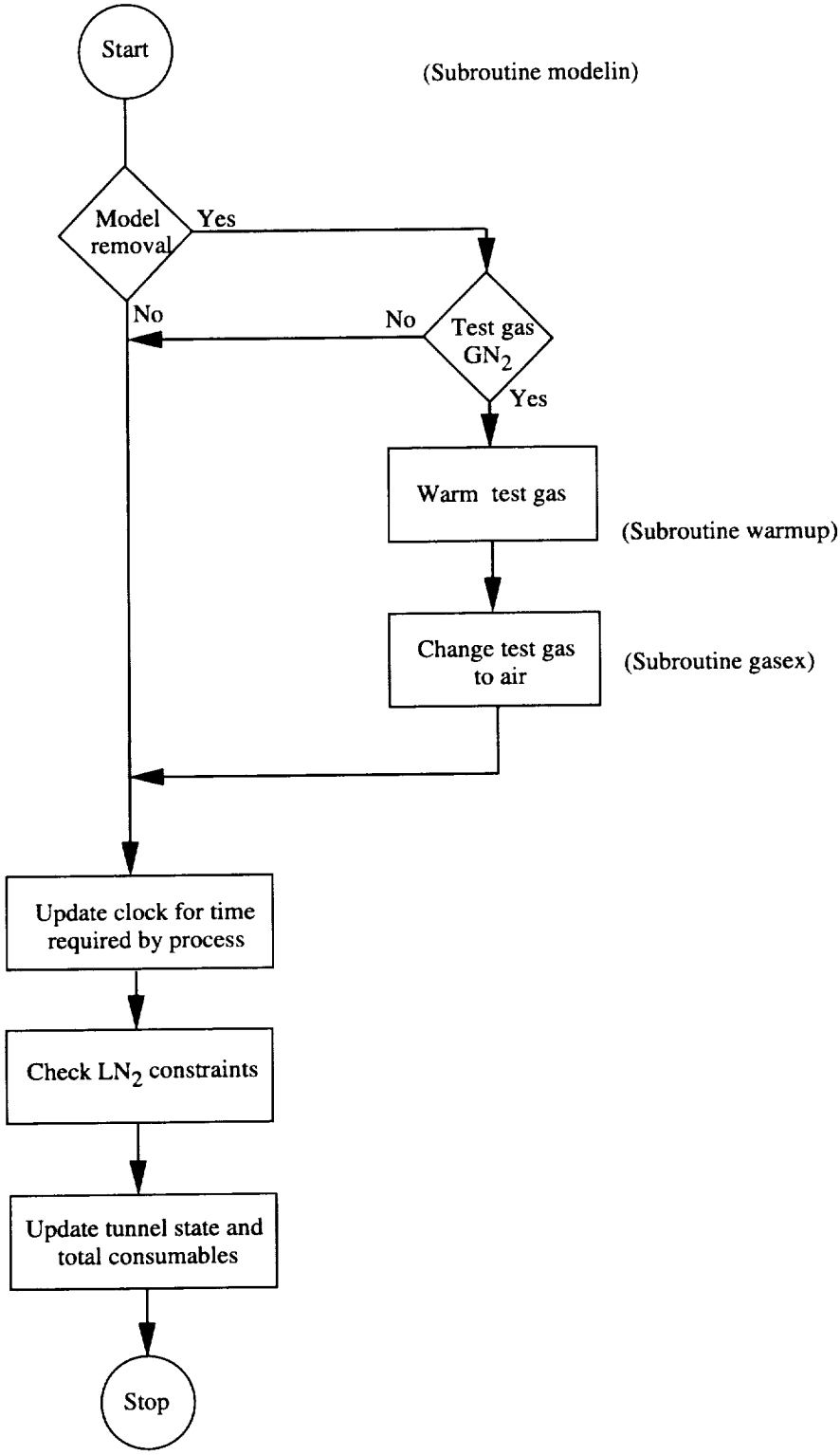


Figure 3. Flowchart of model installation and removal processes.

Tunnel Run

The tunnel run process models wind tunnel operation in which a series of tunnel test conditions are set (tunnel test conditions are assumed to be constant for each polar or angle-of-attack sweep) and data are acquired for each angle of attack in the polar. A flowchart of the logic for a tunnel run is presented in figure 4 below. Two types of tunnel runs can be modeled: operations in the air mode and operations in the GN_2 mode. The type of tunnel run is determined by the tunnel stagnation temperature for the proposed wind tunnel test condition (parameter **ttemp**) relative to a threshold temperature (parameter **tt1**). Figure 5 shows temperature parameters used by the simulator. If the tunnel temperature for the proposed test condition is lower than the threshold temperature, a GN_2

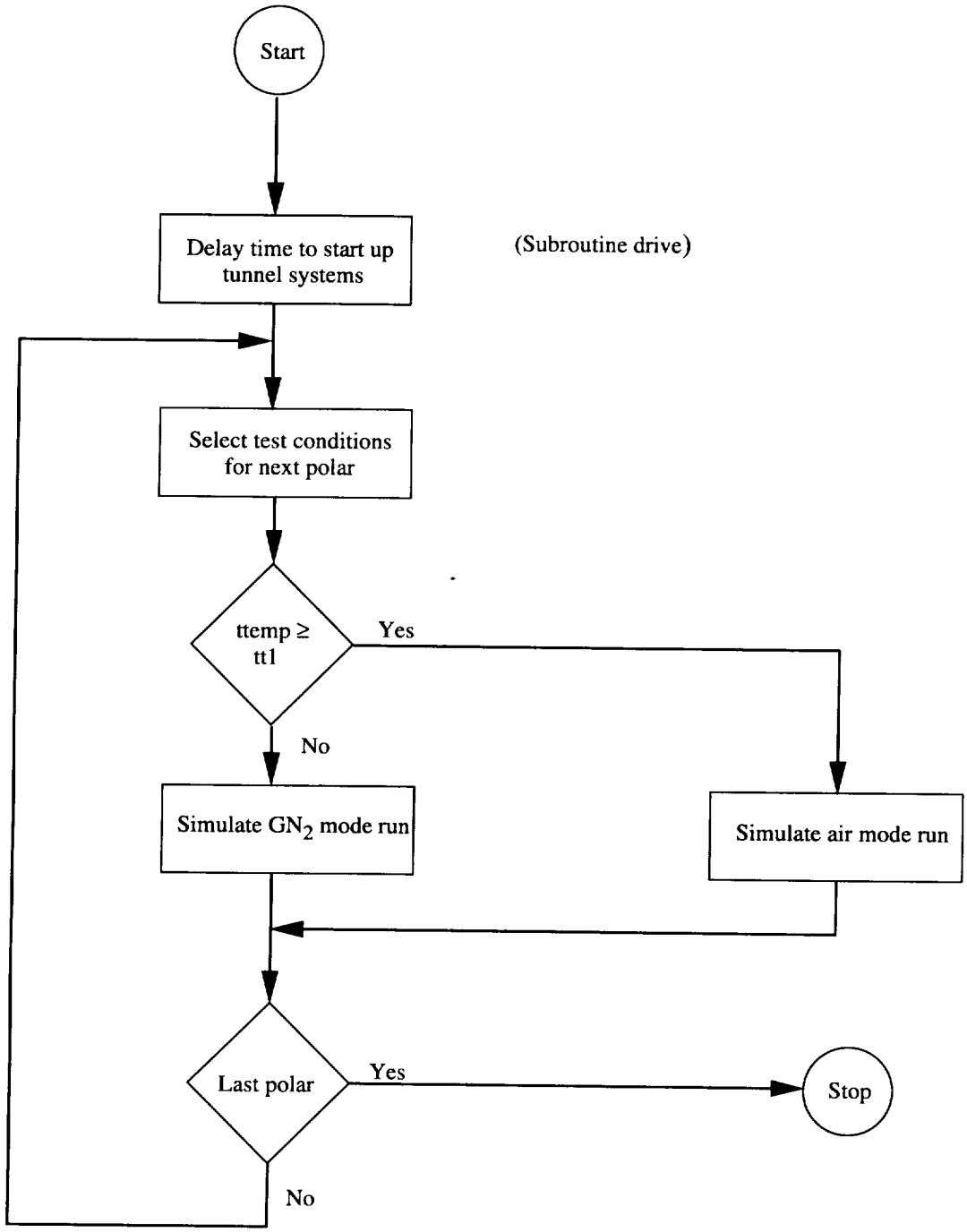
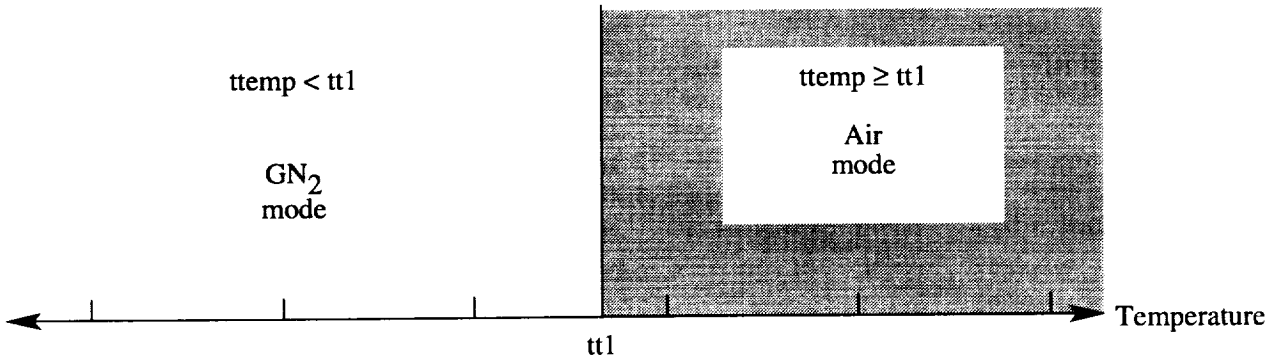
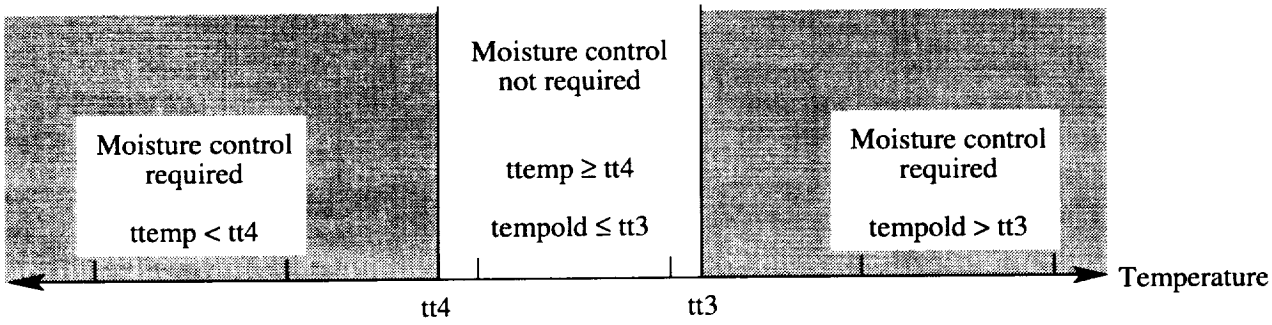


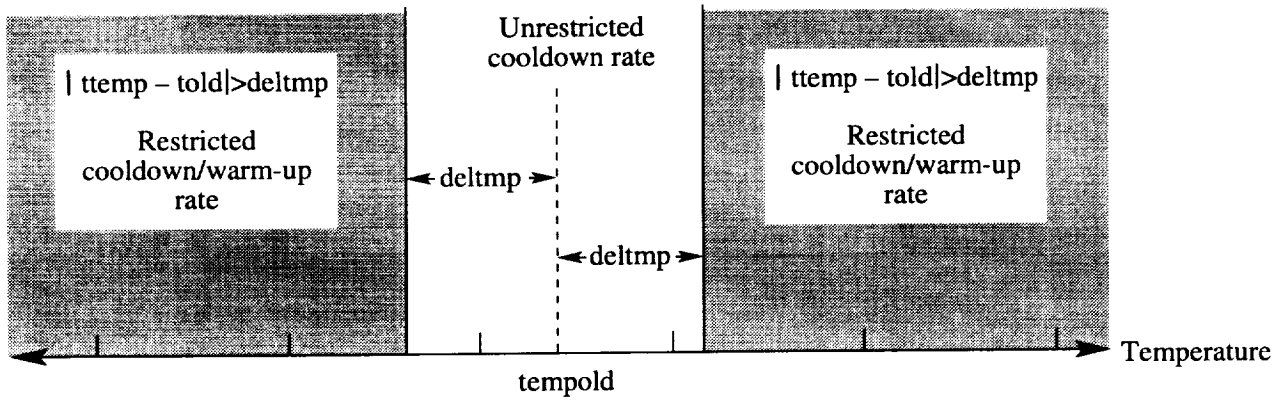
Figure 4. Flowchart for tunnel run process.



(a) Tunnel operations mode.



(b) Moisture control.



(c) Cooldown rate.

Figure 5. Temperature parameters used by simulator.

run will be simulated; otherwise, an air run will be simulated. (See fig. 5(a).) Different processes are used to simulate the two types of tunnel-testing modes.

Air mode. Various activities must be completed prior to starting a tunnel run in the air mode. A flowchart is presented in figure 6 that shows activities associated with tunnel operations in the air mode. For an air mode tunnel run, an automatic process simulates the time required to start up the various tunnel systems (parameter **tsup**). If the tunnel operations mode for the last process was for GN_2 operations, additional automatic processes are initiated to model the activities required to switch from the GN_2 operations mode to the air operations mode. First, the test gas (GN_2) is warmed to the temperature (parameter **airtmp**) required to begin the gas

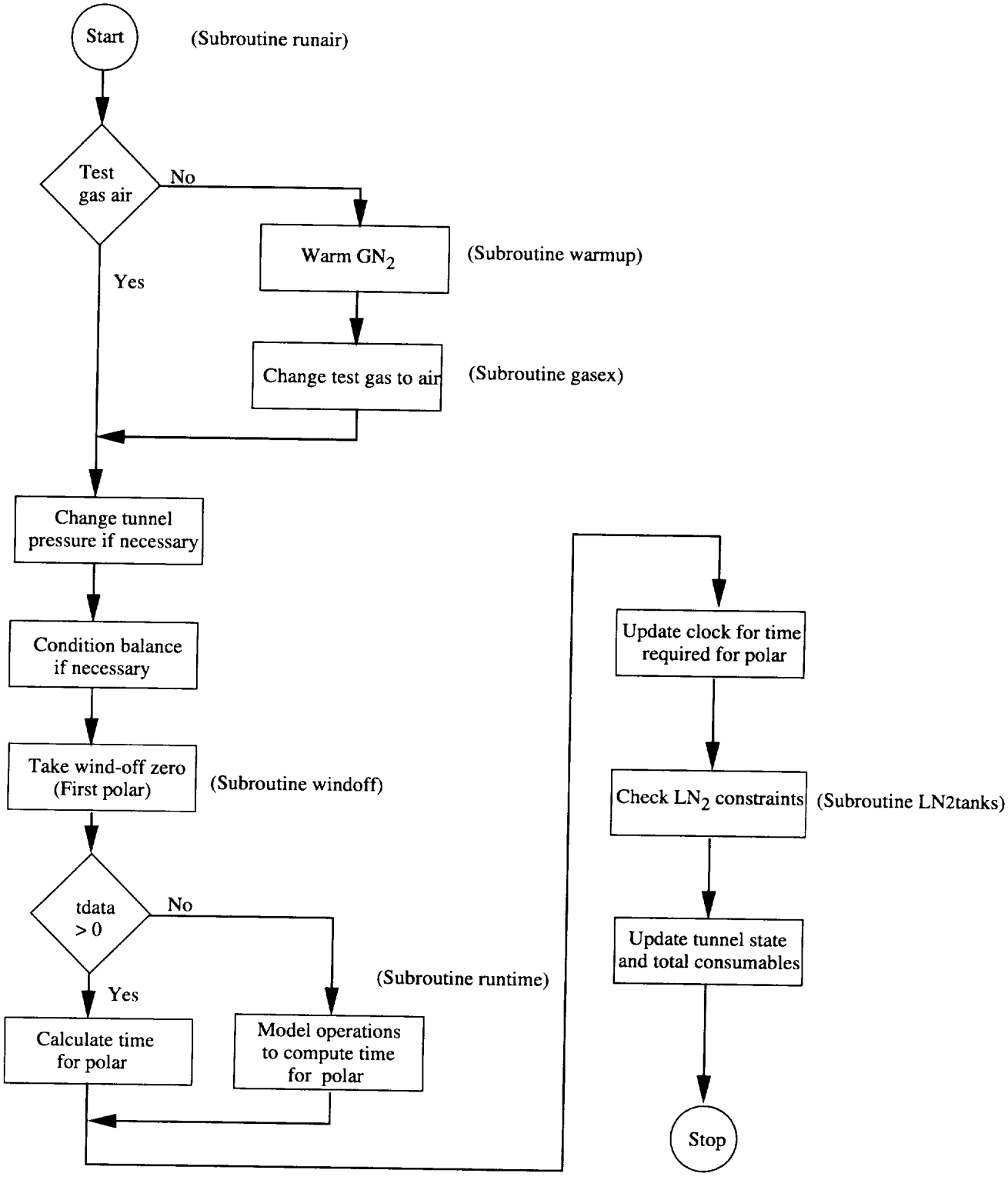


Figure 6. Flowchart of tunnel run in air mode.

exchange. The gas exchange from GN_2 to air then takes place. (See the "Warm-Up" and "Gas Exchange" sections.) Fan operations are delayed to pressurize the tunnel to the pressure (parameter **pt**) of the first polar in the proposed tunnel run. The time to pressurize the tunnel is determined from the required change in pressure (the difference between **pt** and **ptstart**) and the tunnel pressurization rate (parameter **prate**). Electricity and LN_2 are not consumed during the simulated pressurization. If the temperature for the first polar differs from the current test gas temperature by more than parameter **deltmp**, the balance-conditioning process is used to reduce problems associated with thermal gradients in the balance. (See the "Balance-Conditioning" section.) Finally, the wind-off-zero process is initiated. After these processes are complete, the air mode tunnel run is processed.

Each polar specified for the tunnel run is processed in sequence. The time for the polar is determined in one of two ways, depending on the user specified value of the average data acquisition time per data point (parameter **tdata**). If **tdata** > 0, the time is simply the product of the average time per data point (parameter **tdata**) and the number of angles of attack for the polar (parameter **aoasch** from the angle-of-attack schedule for the current polar). Otherwise, if **tdata** ≤ 0, the time is obtained from the data acquisition simulation algorithm. The electrical use rate (parameter **fpow** from the test conditions schedule) is obtained from the test condition file. No LN_2 is consumed for tunnel runs in the air operations mode. If there is sufficient shift time remaining, the polar is simulated, and the time and the consumable variable states are updated. If there is not sufficient time, a downtime extending until the end of the workday is inserted into the test plan. The downtime is added to the total for this lost time (insufficient time to complete the polar or process) category.

GN_2 mode. Various activities must be completed prior to starting a tunnel run in the GN_2 mode. A flowchart of activities associated with tunnel operations in the GN_2 mode is presented in figure 7. For a GN_2 mode tunnel run, an automatic process models the time (parameter **tsup**) required to start the various tunnel systems. If the operational mode for the last process was for air operations, additional automatic processes are used to model the events that are required to change to GN_2 operations. First, the cooling coils are drained and dried. A gas exchange from air to GN_2 then takes place. Details of these processes can be found in the section describing the automatic processes. A check determines whether there is sufficient time to lower the dew point (if required), cool the test gas, condition the balance, acquire a wind-off zero, and have at least 1 hour left before the end of the workday for data acquisition. If there is not sufficient time, a downtime extending to the end of the workday is inserted into the test plan. The downtime is added to the total for this category (insufficient time to complete a cooldown). If there is sufficient time to complete these activities, additional automatic processes are used to prepare for the GN_2 mode tunnel run. If the dew point in the test gas is too high, the moisture reduction (dew point) procedure is required. The moisture reduction procedure is required if the current test gas temperature (parameter **tempold**) has risen above a threshold (parameter **tt3**) and the temperature of the proposed tunnel test condition (parameter **ttemp**) is below a frost threshold (parameter **tt4**). (See fig. 5(b).) After the moisture reduction procedure is complete, either the cooldown or the warm-up process may be used to change the test gas temperature to the temperature for the next polar in the tunnel run. If the temperature change is greater than maximum unrestricted temperature change (parameter **deltmp**), the appropriate process to implement the temperature change is used; otherwise, the time to change the temperature is included in the data acquisition process. The balance is conditioned to reduce problems associated with thermal gradients in the balance whenever the magnitude of the temperature change is greater than the unrestricted temperature change. After thermally conditioning the balance, the wind-off-zero procedure is performed for the first polar in the tunnel run. In that procedure, the fan is stopped and the test gas is allowed to reach a stagnant (zero velocity) condition; the ESP system undergoes a full calibration, a set of wind-off-zero readings are recorded, and the fan is brought back on-line. After these automatic processes are complete, the GN_2 run is processed. Note that the wind-off-zero procedure is modeled as a single block of time (parameter **tonoff**). The fan-drive system is operational, and both electricity and LN_2 are consumed during part of this time. As an approximation, the LN_2 and electricity consumption rates used during the balance conditioning are assumed to extend through the wind-off-zero process.

Each polar in the GN_2 tunnel run is processed in sequence. The time required to complete a polar is determined in the same way that was used for an air tunnel run. If **tdata** > 0, the time is simply the product of the average time per data point (parameter **tdata**) and the number of angles of attack for the polar (parameter **aoasch** from the angle-of-attack schedule for the current polar). Otherwise (if **tdata** ≤ 0), the time is obtained from the data acquisition simulation algorithm. The LN_2 consumption and the electrical use rate are obtained from the test condition file. If there is sufficient time remaining in the workday and sufficient LN_2 in the tanks to complete the polar, the polar is simulated and the consumable variable states are updated. If there is insufficient time, a downtime to the end of the workday is

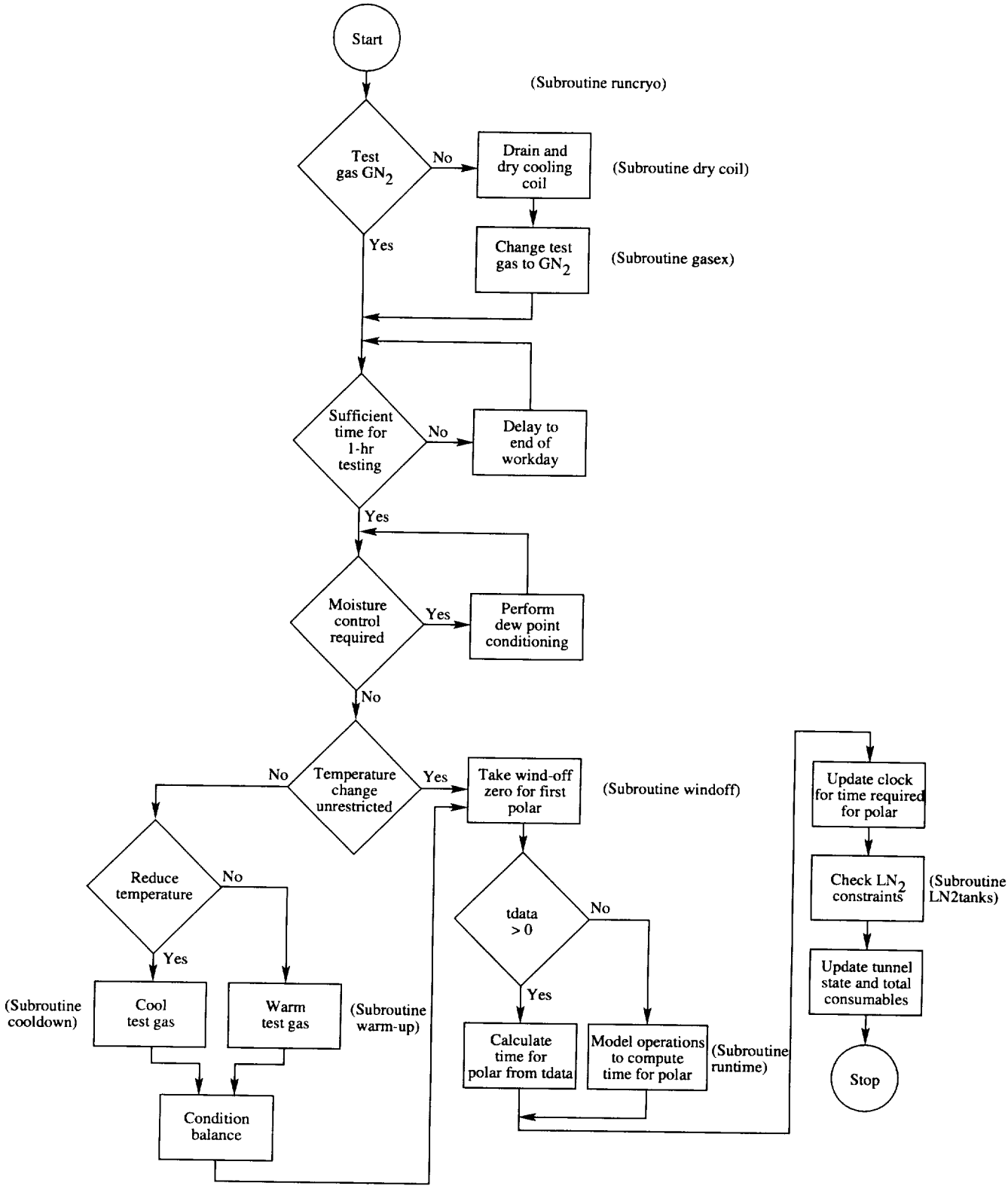


Figure 7. Flowchart of tunnel run in GN_2 mode.

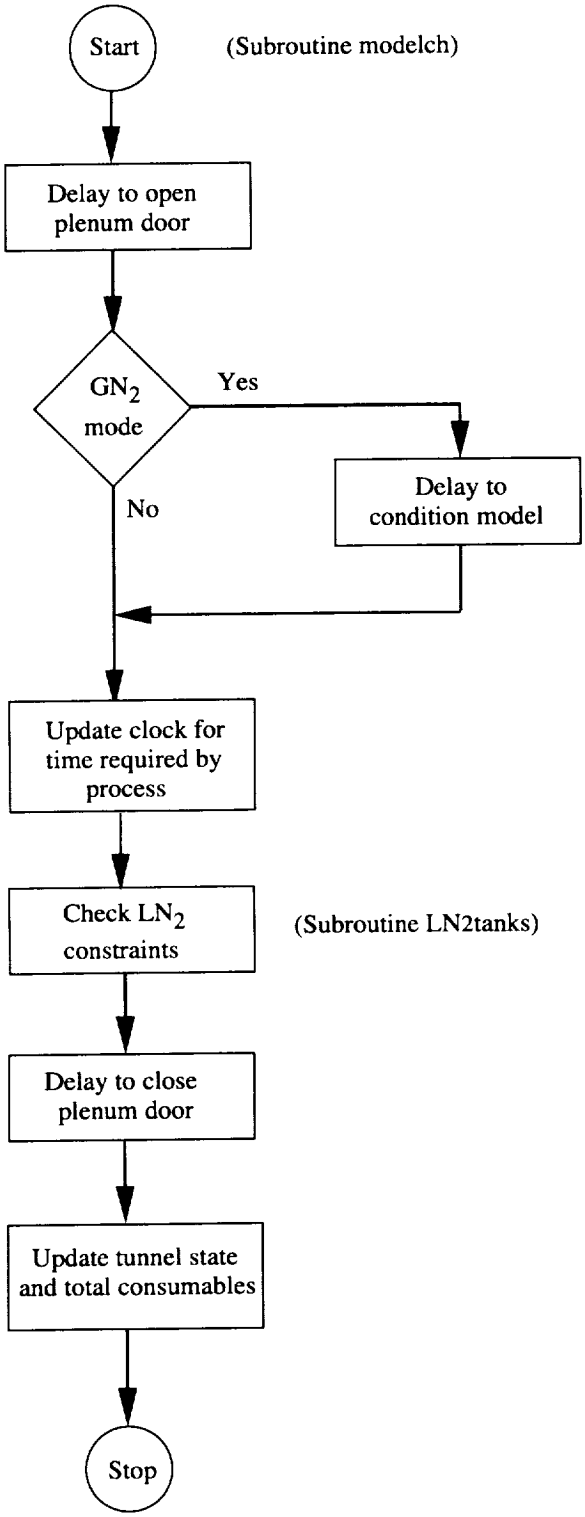


Figure 8. Flowchart of model change process.

inserted and the time is added to the total time lost at the end of the day. During this time, the heat transfer from the shell and the use of high-pressure air for the access housings are modeled. If there is insufficient LN_2, a delay to refill the on-site operations tank is inserted. The lost time is added to the total time that operations were delayed for the lack of LN_2.

Model Change

A flowchart of the logic used to simulate the model change process is presented in figure 8. The model change process is simulated by a user specified block of time in hours. The model change time begins when the model has been warmed so that it can be handled and ends when the access housings can be removed. Before the model change process is simulated, one or two automatic processes are completed. The first process simulates the opening of the tunnel plenum doors and the insertion of the model access housings. The time for this process is specified by the user in parameter **tacc**. A second automatic process may be needed to warm (condition) the model so that it can be handled if the tunnel operations mode for the last polar was in the GN_2 operations mode. The time required for this process depends on the model conditioning rate (parameter **tmcrate**) and the required model temperature change. The initial model temperature is assumed to be the same as the test gas temperature at the end of the last process. The final temperature is assumed to be 70°F. Once these processes are complete, the model change is simulated by a simple delay. After the model change, the removal of the access housings and the closing of the plenum doors are simulated by an automatic process. During each of these processes, heat transfer from the shell and the use of high-pressure air for the access housings are simulated for GN_2 operations. Electricity and LN_2 are not used during this commanded process or any of the required automatic processes. If the time needed to complete any of these processes extends past the end of the workday, the process is continued at the start of the next workday.

Holiday

The holiday process accounts for workdays on which the facility is not staffed for operations. A flowchart of the holiday process is presented in figure 9. During a holiday, there are no tunnel operations. However, both heat transfer from the shell and the use of high-pressure air for the access housings are simulated for GN_2 operations. Electricity and LN_2 are not used during this process. The holiday downtime is modeled by a delay for the specified number of workdays (not hours).

Tunnel Downtime

During certain periods of annual maintenance, tunnel inspections, system failure, or hardware installation, the NTF is not available for operations. These periods are simulated by the tunnel downtime process. A flowchart

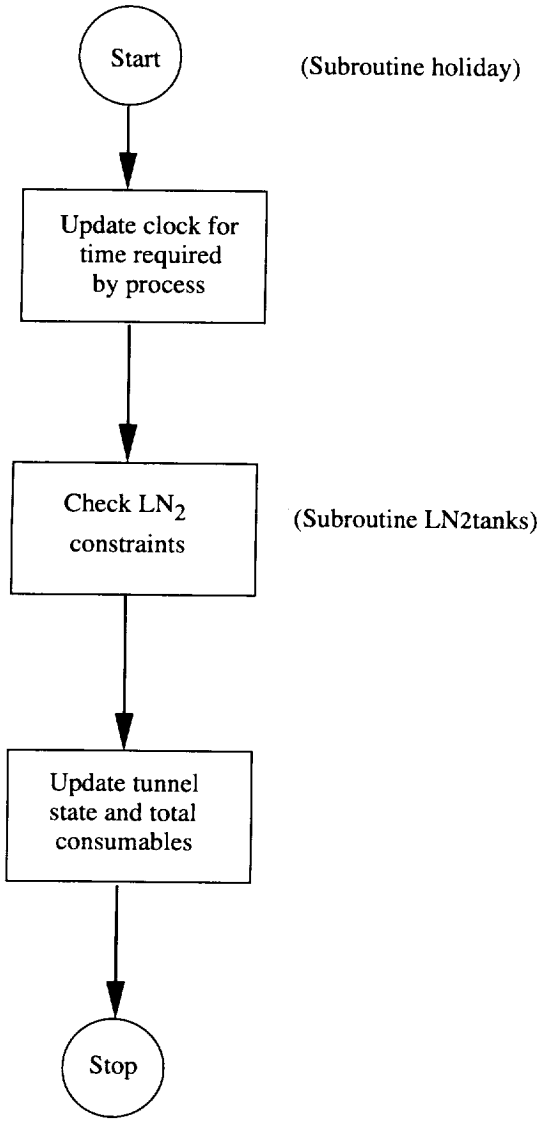


Figure 9. Flowchart of holiday stand-down process.

of the tunnel downtime process is presented in figure 10. An option is available to change the test gas in the tunnel circuit before starting the process. If this option is selected and the current mode is for GN_2 operations, the test gas is first warmed and then a gas exchange to air is modeled. During the downtime, LN_2, electricity, and high-pressure air are not used.

Automatic Processes

Certain commanded processes require that special conditions be met before the commanded process is performed. Logic has been added to the commanded processes to use automatic processes whenever the special conditions have not been met. Note that during all processes, LN_2 production and delivery are simulated. This section describes these automatic processes.

Cooling Coil Drying

When operations change from air mode to GN_2 mode, the cooling coils must be drained and any remaining moisture must be removed. If the last tunnel operation was in the air mode and the next operation is in the GN_2 mode, a time delay is inserted to perform this process (parameter **tdry**). Electricity, LN_2, and high-pressure air are not used during this process.

Start-Up Procedures

Operational procedures must be completed prior to the start-up of the tunnel. The time required, determined from user input (parameter **tsup**), is modeled as a simple delay. If the tunnel is in the GN_2 mode, both the heat transfer from the shell and the use of high-pressure air for the access housings are simulated. Electricity and LN_2 are not used during this process.

Gas Exchange

When the operations mode changes between consecutive tunnel operations, the test gas must be changed. When going from air to GN_2, the time for the exchange (parameter **tgn2**), the LN_2 flow rate (parameter **volln2**), and the electrical use rate (parameter **volpow**) are used to model the process. No high-pressure air is required. When going from GN_2 to air, the time required for the exchange (parameter **tair**) and the electrical use rate (parameter **airpow**) are used to model the process. No LN_2 is required. The required high-pressure air is determined from the number of pressure cycles (parameter **cycles**), the air required for each pressure cycle (product of the parameters **deltap** and **airm**), and the tunnel pressurization rate (parameter **prate**). If the gas exchange cannot be completed before the end of the workday, a delay until the end of the workday is inserted. The lost time is added to the total time that is lost because a process could not be completed before the end of the workday.

Moisture Control (Dew Point Conditioning)

The dew point conditioning process is used to lower the dew point before cooling the test gas. This process is used only for GN_2 operations to minimize the development of frost on the model. Dew point conditioning is required when the gas temperature of the next tunnel test condition (parameter **ttemp**) is less than the minimum threshold temperature (parameter **tt4**) and the previous test gas temperature (parameter **tempold**) is greater than the maximum threshold temperature (parameter **tt3**). (See fig. 5(b).) Dew point conditioning is not required if the previous process was a gas exchange from air to GN_2. The time required to complete the process (parameter **tdew**), the LN_2 flow rate (parameter **dewln2**), the

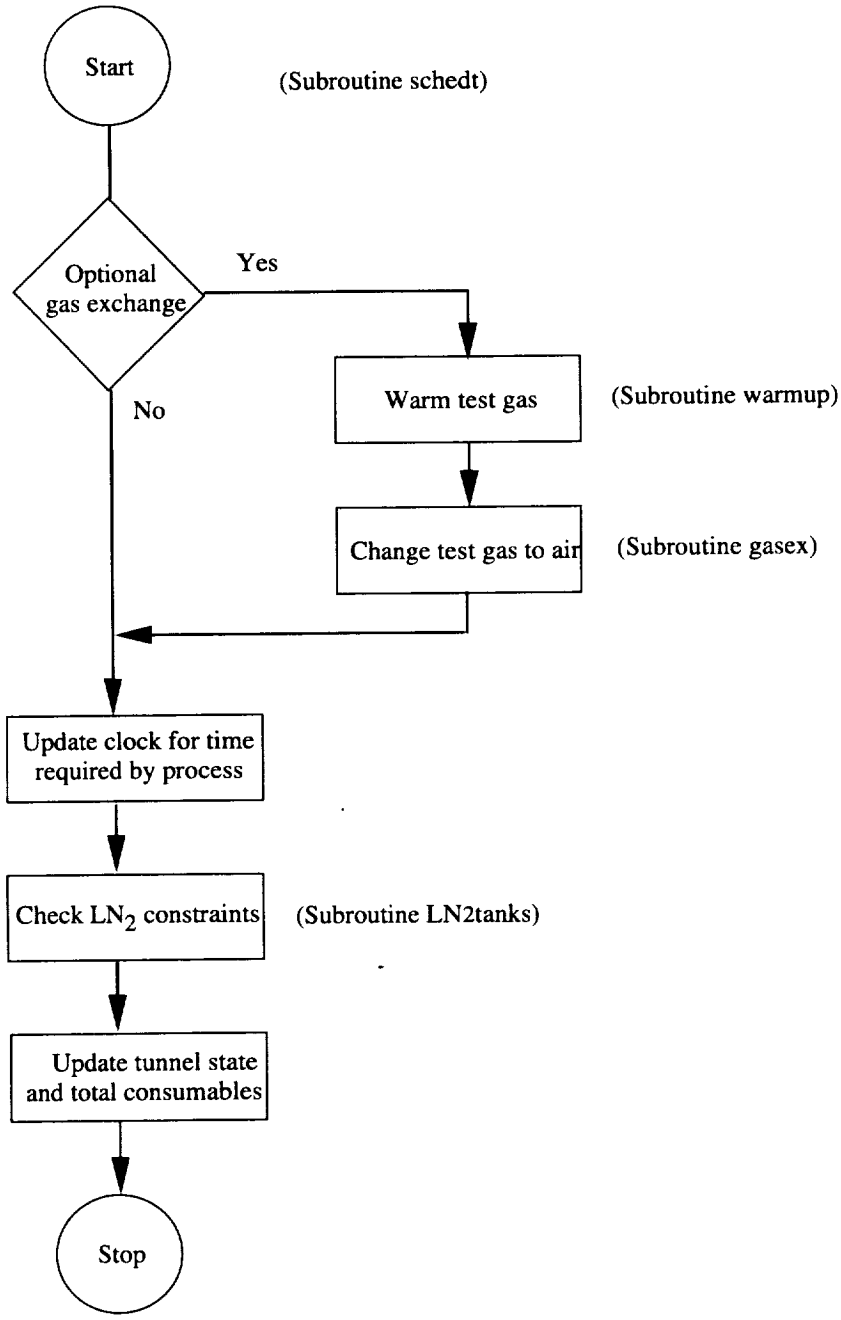


Figure 10. Flowchart for tunnel downtime.

electrical use rate (parameter **dewpow**), and the high-pressure air use rate (parameter **accair**) are used to model the process. If the process cannot be completed during the workday, a downtime is inserted that lasts until the end of the current workday. The lost time is added to the lost-time total at the end of the workday.

Cooldown

The cooldown process is used only for GN_2 operations. If the current test gas temperature is greater than the temperature for the first test condition, the test gas must be cooled. Because of limitations placed on thermal gradients in the tunnel structure, the maximum cooldown rate of the test gas is restricted for large changes in the test gas temperature between two consecutive test conditions (parameter **ttemp-told**). (See fig. 5(c).) For changes in the test gas temperature exceeding the maximum (parameter **deltmp,** currently 50°F), the cooldown process must be used. Otherwise, for changes less than or equal to the maximum, the cooldown rate is not restricted by the tunnel structure, and the time to change the

temperature (and all the test conditions) is modeled in the data acquisition process. For this situation, please refer to the section describing a tunnel run.

The maximum cooldown rate is determined by the temperature gradient that the tunnel structure can safely withstand. A plot of the assumed pump output flow rate and the test gas cooldown rate, as a function of the gas temperature, is presented in figure 11. The variables (parameters) used to define these relationships are noted on the figure. The values shown for the different variables are typical of current experience at the NTF. At a temperature of 100°F, the LN_2 flow rate (parameter **cllnmin**) of 200 gpm is just sufficient to cool the tunnel gas down at the current maximum cooldown rate (parameter **clrtmax**) of −72°F/hr. The pump output increases linearly to its maximum value (parameter **cllnmax**) of 400 gpm to maintain the maximum cooling rate down to a gas temperature (parameter **clstar**) of −200°F. At temperatures below −200°F, the maximum pump output is maintained but the cooling rate (parameter **clrtmin**) decreases linearly to −36°F/hr as the temperature is reduced to −250°F. During the cooldown process, high pressure air is used for the access housings. The fan-drive power (parameter **coolfp**) is typically 1.5 MW during the cooldown. The algorithm determines the time required to complete the cooldown from the assumed variation of the cooldown rate with temperature and the initial and final temperatures. The electrical use is the product of the fan-drive power and the time required to complete the cooldown. The required LN_2 is determined from the flow rate and the calculated cooldown time. The average flow rate is the quotient of the required LN_2 and the cooldown time. This process should not be interrupted by the end of the workday. A check ensures that there is sufficient time to complete the process before it is started.

Warm-Up

If the current test gas temperature is less than the temperature for the first test condition of a GN_2 run, or if a volume exchange from GN_2 to air is required, the test gas must be warmed. As was discussed above, for a test gas cooldown, a restricted warm-up rate is required for large changes in test gas temperature (exceeding parameter **deltmp**). (See fig. 5(c).) The process completion time is determined from the required change in the gas temperature and the tunnel warm-up rate (parameter **wrmrat**). If the warm-up is needed prior to a gas exchange, the final temperature is determined from the simulation input (parameter **airtmp**). The fan-drive power (parameter **wrmpow**) and high-pressure air use rate (parameter **accair**) are determined from the simulation input. No LN_2 is used. If the process cannot be completed before the end of the workday, the process is continued on the next workday.

Balance Conditioning

The balance must be temperature-stabilized to minimize balance electrical output signal shifts due to temperature gradients in the balance which occur after a large change in the test gas temperature. The time required to condition the balance is determined from the simulation constant input (parameter **balcon**). Balance conditioning follows the completion of a cooldown or warm-up process. For GN_2 operations, the LN_2, electrical, and high-pressure air use rates are the same as those that were just used for the preceding cooldown or warm-up process as an approximation. For air operations, the LN_2, electrical, and high-pressure air use rates are the same as those that are defined for the gas exchange process from GN_2 to air operations mode.

Wind-Off Zero

Once the balance has been conditioned, the wind-off-zero process is executed. The process represents several individual operations with a single block of time and average consumption rates. In the sequence of events the fan is stopped and the test gas is allowed to come to stagnant (zero velocity) conditions; a wind-off zero is recorded for the instrumentation, a full calibration is completed for the ESP system, and the fan is brought back on-line. The LN_2, electrical, and high-pressure air use rates are the same as those that are defined for the balance conditioning process. The time for the wind-off-zero process is determined from the input (parameter **tonoff**).

Support Algorithms

Tunnel Structure Heat Transfer

For cryogenic operations, the test gas temperature is colder than the tunnel structure temperature. For these situations, heat is transferred from the tunnel structure to the test gas. The heat transfer rate decreases as the difference between the tunnel structure temperature and the test gas temperature decreases. Since the temperature of the external tunnel structure is relatively constant, the temperature difference decreases as the test gas warms up. Because the heat transfer rate decreases with time in a manner similar to a decaying process, the following exponential equation was selected to describe the average rate of temperature change with time:

$$\dot{T} = c\, e^{\tau}$$

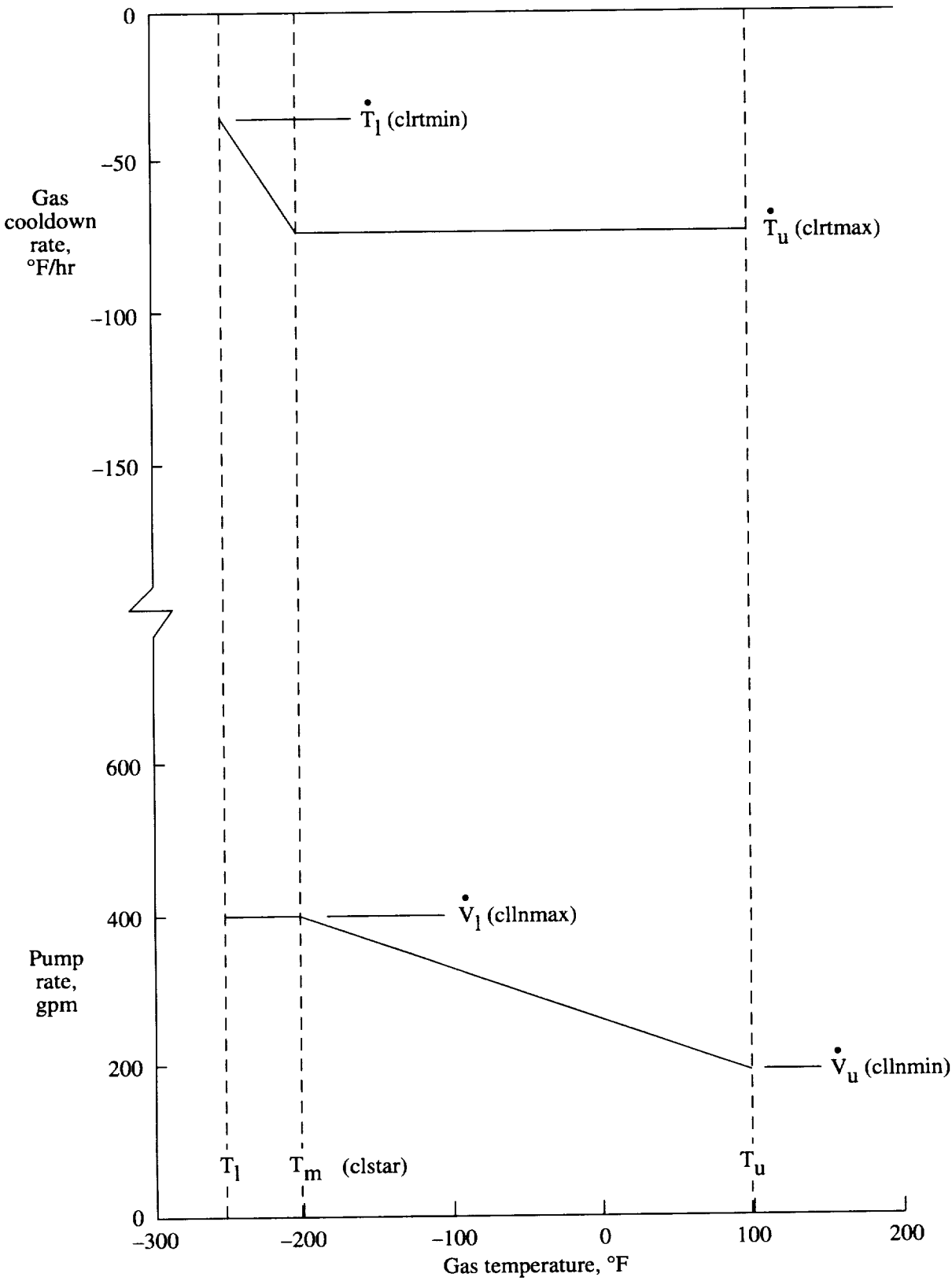


Figure 11. Assumed cooldown process.

where

$$c = c_1 - \sqrt{T + 460}$$

$$\tau = a \cdot t^2 + b \cdot t$$

The variation of the test gas temperature (with time) was recorded as the test gas warmed up naturally (no heat addition from the drive fan). This time history was used to define the three empirical constants (a, b, and c_1). Three different conditions (times) were selected to characterize the test gas warm-up rate. The maximum warm-up rate observed immediately after operations ceased (time = 0 hr) at $T = -250$°F was about 15°F/hr. The average warm-up rate overnight (time = 15 hr) was about 10°F/hr. The average warm-up rate over a weekend (time = 60 hr) was about 5°F/hr. Using these warm-up rates and times, the following values were obtained for the empirical constants: $a = 0.185 \times 10^{-3}$, $b = -0.029444$, and $c_1 = 24.0$.

Data Acquisition

For most test plans with about 25 points per polar and moderate changes in test conditions between polars (requiring an average of about 3 min), an average time per data point (parameter **tdata**) of 26 sec is adequate to simulate the time spent acquiring the data for a single data point in a polar. However, if the number of points per polar differs significantly from 25, or the time required to change test conditions is significantly different from 3 min, the time spent for each polar needs a more detailed simulation. In this case, the time spent on a polar is modeled by several steps. This situation requires the input of the optional data acquisition parameters at the end of the simulation parameters input file. The modeled steps are pitch the model to 0°, change the test conditions, roll the model (if required), acquire an ESP zero calibration (every polar), and for each angle in the AOA schedule, repetitively pitch the model, fine-tune the tunnel test conditions, allow transients to damp out, and acquire the data. The time required to pitch the model is simulated using a pitch rate (parameter **dthetadt**), the required change in pitch angle, and a settling time (parameter **tsetlalpha**). The time to change test conditions is assumed to be constant (parameter **tchtcon**). In practice, the time to change test conditions depends on the current and the next test conditions. However, an internal calculation of the time to change the test conditions was beyond the scope of this project and should be considered a future modification of the simulator code. The time required to roll the model is simulated using a roll rate (parameter **dphidt**), the required change in model roll angle, and a settling time (parameter **tsetlphi**). The times to obtain a zero calibration of the ESP system (parameter **tzcalib**), to fine-tune the test conditions (parameter **tsetlmach**), to allow the data to settle (parameter **tsetltube**), and to acquire the data (parameter **tacquis**) are all fixed times for a given simulation.

LN_2 Supply System

The computer model allows either two or three LN_2 tanks to be used in the simulation. A sketch of the assumed tank configuration is presented in figure 12. The current configuration consists of two tanks: the manufacturer's supply tank and the NTF operations tank. The optional third tank has been included in the simulator to support productivity improvement studies involving the addition of an extra storage tank. The first tank, referred to as the supply tank, is located at the manufacturer's site and is filled at a production rate (parameter **ratepro**) that varies from about 11.2 ton/hr in the summer to about 13.5 ton/hr in winter. Since the simulator assumes a constant production rate, an average value for the test should be specified. If the time of year for the test has not been fixed, an average value of 12.5 ton/hr should be specified. The supply tank has a capacity of 2679 ton (parameter **capsup**).

The second tank, referred to as the operations tank, is located on-site to supply LN_2 directly to the NTF, and it may be filled from one or both of the other tanks. Liquid nitrogen is drawn from the operations tank at the use rate specified for the current process. The operations tank has a capacity of 893 ton (parameter **capops**). The upper limit of this tank is 95 percent of the tank capacity and the lower limit is 10 percent of the tank capacity.

The optional third tank (not in existence at this time), referred to as the storage tank, may be located at either site. This optional tank is included in the LN_2 supply system if it has a nonzero capacity (parameter **capsto**). It will be filled from the manufacturer's supply tank and will provide LN_2 to the operations tank at a fixed transfer rate (parameter **ratetra**) that averages 260 ton/hr. Note that the rate is internally set to zero if the optional storage tank is not used so that the losses in the pipes can be properly calculated. Liquid nitrogen may be delivered from the manufacturer's supply tank to only one tank at a time at a rate (parameter **ratedel**) that can range from about 35 ton/hr to 55 ton/hr, depending on the liquid level in the manufacturer's supply tank and the pump that is selected to transfer the LN_2. Since the actual transfer rate cannot be determined ahead of time, an average delivery rate of 45 ton/hr should be used. The model provides for losses in transfers at a rate of 0.333 ton of LN_2 per hour of transfer. Losses in the storage and operations tanks are 0.25 percent of the tank capacity per day.

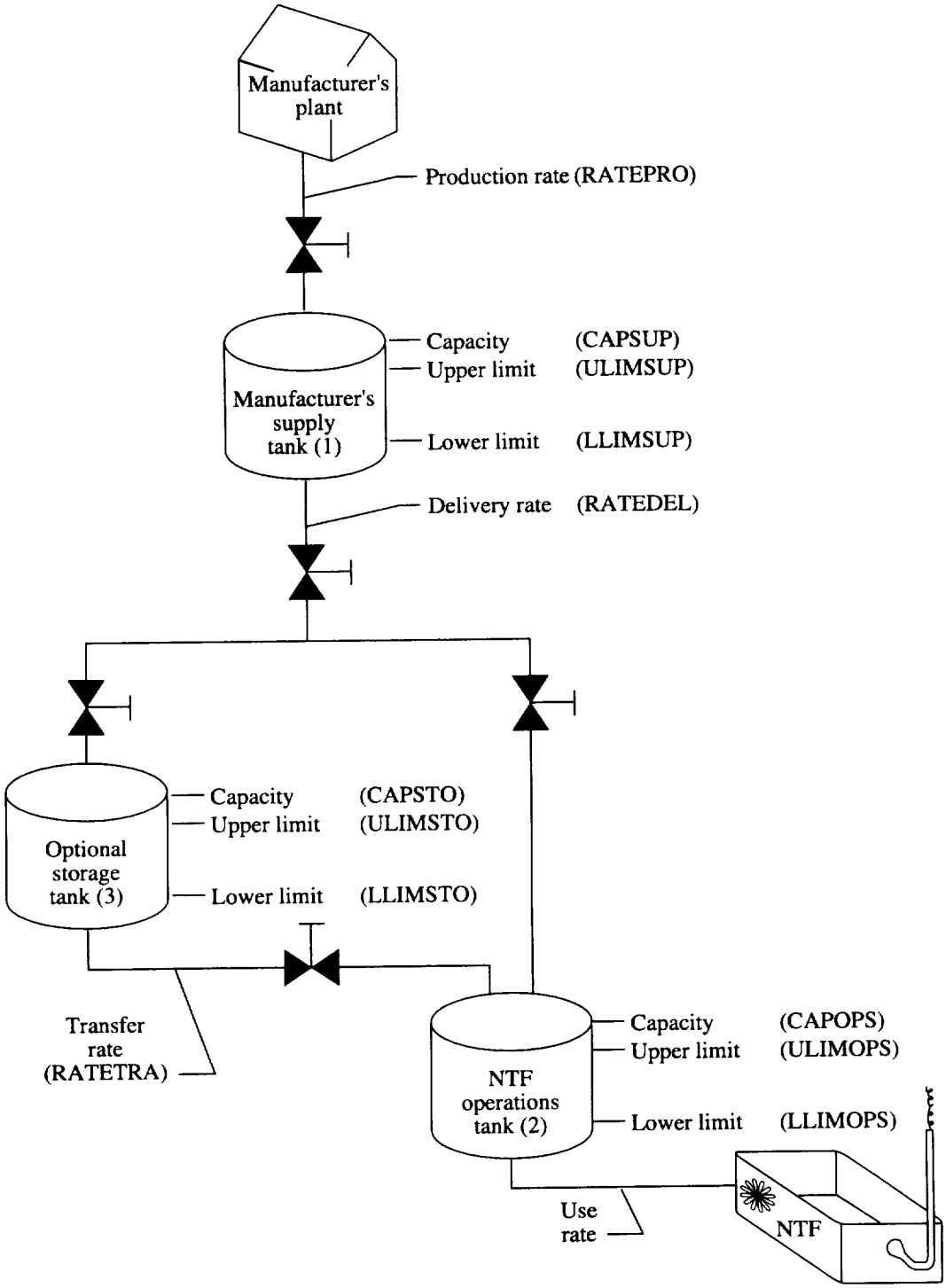


Figure 12. Sketch of LN_2 supply system.

NTF Simulation Model Calibration

The computer model was used to simulate the testing of three aircraft models that were previously tested at the NTF: a high-speed civil transport (HSCT) model, a commercial transport (Boeing 767) model, and a military transport (U.S. Air Force C-17) model. Comparison of results from these three wind tunnel tests at the NTF with results from the simulation program are presented to assess the validity of the NTF simulation model. For these cases, the minimum level in the manufacturer's supply tank was 1 percent of the tank capacity and the maximum level was 99 percent of the tank capacity. These three cases were reviewed to determine that a minimum operations tank refill level of 70 percent of the tank capacity is needed to avoid interrupting a tunnel run more than once to refill the operations tank.

HSCT Test

The test log for the HSCT model was used to develop the test plan file for the simulation program. The file included time for a holiday shutdown as well as time to correct a hardware failure. Since the NTF test data covered only the time from the end of the model installation to the beginning of the model removal, no simulation of the model installation or the model removal was included in the test plan file. The baseline values of the simulation program constants and parameters, presented in the input description in appendix B, were used. The simulation program was used to predict the consumed LN_2, the consumed electricity, the fan-on time, and the occupancy time. The simulation results are compared to the actual NTF test results in table 1. The simulation model underpredicted the value of each parameter being compared. The agreement of the LN_2 and electrical consumption is reasonable, within about 8 percent. The agreement of the fan-on time and the occupancy time is better, differing by about 3 percent.

Table 1. Comparison of Simulation Prediction and NTF Test Results for HSCT Model

Parameter	Simulator	NTF test
LN_2 consumption, ton	9700	10500
Electrical consumption, MWh	773	834
Fan-on time, hr	114	117
Occupancy time, day	36	37

B-767 Test

The test log for the B-767 model was used to prepare a test plan file. Analysis of the test log indicated that the average number of angles of attack per polar was 16. Since this value is significantly different from the number (25) that was used to determine the average time per data point, the average time per data point was not used. For this situation, the detailed simulation of the data acquisition process was used. The baseline values of the input parameters presented in appendix B were used. The simulated and actual results are presented in table 2. No data were available for the actual fan-on time for the NTF test since that information was not recorded when the test was run. Use of the detailed simulation of the data acquisition process produced reasonable agreement with the NTF results. The simulation model overpredicted the LN_2 consumption by about 5 percent and underpredicted the electrical consumption by about 20 percent. The reason for the large difference in the electrical consumption is not known.

Table 2. Comparison of Simulation Prediction and NTF Test Results for B-767 Model

Parameter	Simulator	NTF test
LN_2 consumption, ton	7500	7125
Electrical consumption, MWh	797	987
Occupancy time, day	22	25

C-17 Test

The test log for the C-17 model was used to develop the test plan file for the simulation program. The file included entries for model installation, test delays, and model removal. Using the test records, 21 downtimes totaling 87 hours were included in the simulation test plan to match the delays that occurred during the test. Test records were used to determine the actual average model conditioning rate (110°F/hr), the balance conditioning time (1.5 hr), and the average time per data point (31 sec) for this model. With the exception of these three parameters, the baseline values of the simulation program constants and parameters, presented in the input description in appendix B, were used for the simulation. The simulation program was used to predict the consumed LN_2, the consumed electricity, the fan-on time, and the occupancy time. The results are compared to the actual NTF test results in table 3. The simulation

Table 3. Comparison of Simulation Prediction and NTF Test Results for C-17 Model

Parameter	Simulator	NTF test
LN_2 consumption, ton	15000	15700
Electrical consumption, MWh	964	1078
Fan-on time, hr	156	156
Occupancy time, day	60	57

underpredicted the values of the LN_2 and the consumed electricity but overpredicted the tunnel occupancy time. The difference in the LN_2 consumption is about 5 percent and the difference in the electrical consumption is about 11 percent. The difference in the occupancy time is about 5 percent.

Concluding Remarks

A computer model has been developed to simulate the processes involved in the operation of the National Transonic Facility (NTF), a large cryogenic wind tunnel at the Langley Research Center. The simulation was verified by comparing the simulated results with previously acquired data from three experimental wind tunnel test programs in the NTF. The comparisons suggest that the computer model simulates reasonably well the processes that determine the liquid nitrogen (LN_2) consumption, electrical consumption, fan-on time, and the test time required to complete a test plan at the NTF. From these limited comparisons, it appears that the results from the simulation model are generally within about 10 percent of the actual NTF test results. The use of actual data acquisition times in the simulation produced better estimates of the LN_2 usage, as expected. Additional comparisons are needed to refine the constants in the model. The model will typically produce optimistic results since the times and rates included in the model are typically the optimum values. Any deviation from the optimum values will lead to longer times or increased LN_2 and electrical consumption for the proposed test plan. Computer code operating instructions and listings of sample input and output files have been included.

NASA Langley Research Center
Hampton, VA 23681-0001
May 16, 1995

Appendix A

Computer Model Operating Instructions

To use the NTF simulation computer model, the user must prepare the input files and compile the computer model source code to create an executable module prior to using the model. This section describes the type of required input files, the type of generated output files, and the required steps to create an executable module. Additional information concerning the input and output files may be found in the appendixes.

Input Files

A sketch of the data flow associated with the use of the NTF simulator is presented in figure 2. A flowchart of the logic in the computer model is presented in figure A1. Four input files are required by the NTF operations simulation computer program: (1) constants and parameters (parameter **file1**), (2) test conditions (parameter **file2**), (3) angle-of-attack schedules (parameter **file3**), and (4) the test plan or run schedule (parameter **file4**). The constants file contains the input and output file names, the initial conditions for the consumables, and the parameter values that are needed to simulate the different processes. The test conditions file contains the wind tunnel test conditions (Mach number, Reynolds number, stagnation temperature, and stagnation pressure) and the consumable use rates (LN_2 use rate and fan power). The angle-of-attack schedules define a single model roll attitude and the pitch angles in order to be set for a given polar. The test plan file defines each commanded process to be simulated in the test. These four files should be created using any available text editor. Detailed information of the contents and format of each file is found in appendix B. Sample input files are found in appendix C.

Output Files

The program generates two output files: a data file and a plot file. The names of these files are defined in the simulation parameters file. The data file echoes a summary of the simulation parameters file (**file1**), the test conditions file (**file2**), and the angle-of-attack schedule file (**file3**). Information concerning each simulated process follows. For each process, the elapsed time, LN_2 tank levels, and total consumption of electricity, LN_2, and high-pressure air are listed, followed by text describing the current process. A summary of results of the test plan simulation completes the data file.

The plot file contains a single header line with the name of each variable contained in the plot records. Multiple plot records follow, one for each process. The variable names and the values appear in the same order in each record. Additional information about the format of these two files is found in appendix D. A portion of a sample data file is found in appendix E.

Executable Module Preparation

The NTF simulation computer model is coded in FORTRAN 77 and has been run under a UNIX operating system environment. Before creating the executable module, the parameter values used for storage allocation must be defined in the file "*ntfsim.param*". The five parameters defined in that file are described in table A1 below. This file should be edited so that the parameter values satisfy the storage requirements of the input files to be processed.

Table A1. Parameters for Storage Allocation

Variable	Maximum number of—
imax	Test conditions specified in **file2**
jmax	Angle-of-attack schedules in **file3**
kmax	Processes specified in test plan **file4**
lmax	Polars specified per run in **file4**
mmax	Angles of attack in an AOA schedule in **file3**

A *Makefile* is provided to compile and link all the program elements into an executable module *ntfsim.exe*. To create an executable module, change the current directory to that containing the source code and type *make ntfsim* followed by a carriage return. The executable module will be found on the same directory that contains the source code.

Computer Model Execution

The four input files and the executable module should all be moved to the same directory. To run the program, type *ntfsim.exe* followed by a carriage return. The program will prompt the user for the name of the simulation parameters and constants file, **file1**. Type the name of the file followed by a carriage return. The program will write to the terminal screen each commanded process as it is processed from the test plan file. When the program execution is complete, the prompt for the name of the parameters and constants file will be repeated. If another case is to be run, the response is the same as before, that is, the name of the **file1** to be processed; otherwise, type *stop* followed by a carriage return to terminate the program. Note that if multiple cases are run, the levels in the LN_2 tanks at the end of the case that was just completed are used as the initial levels for the next case.

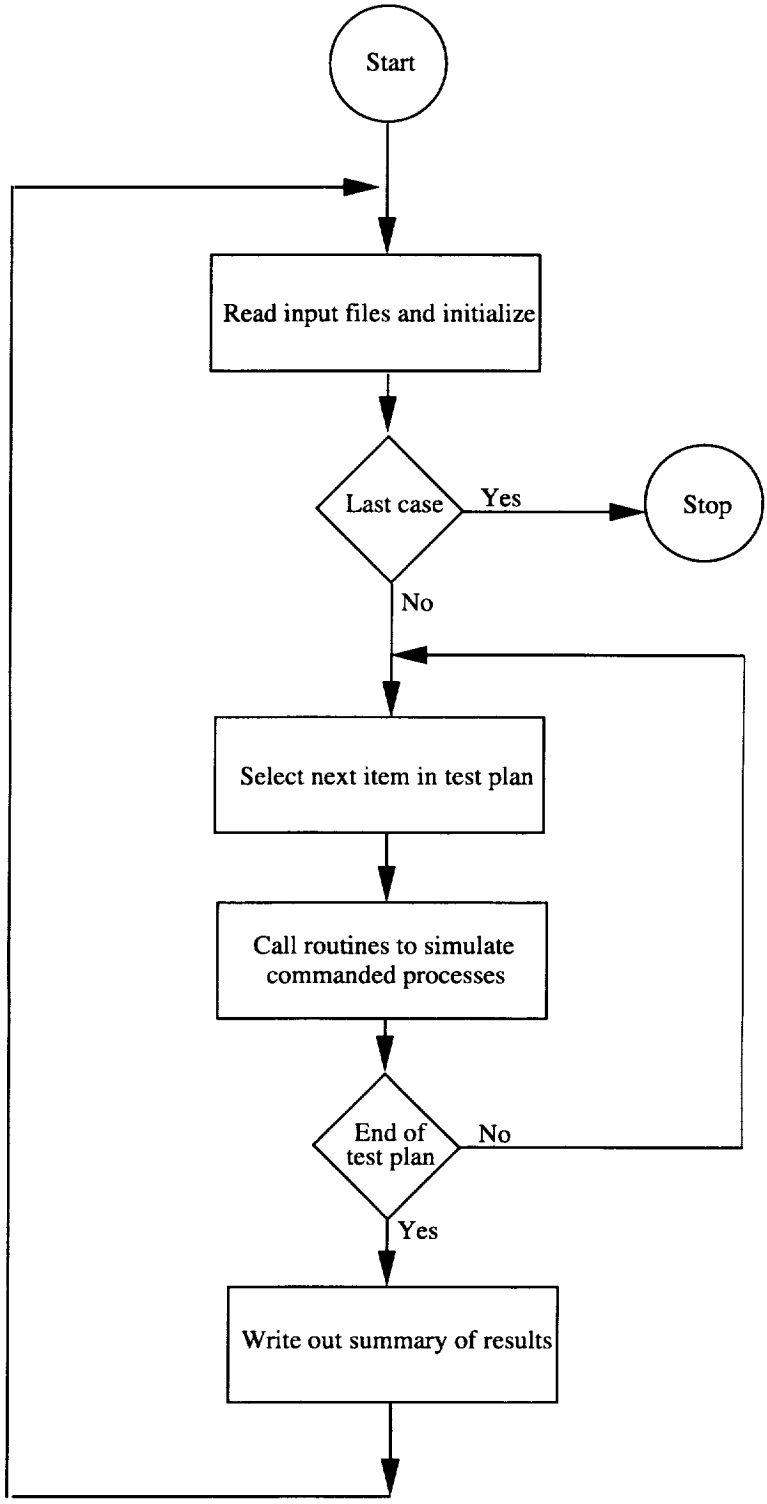


Figure A1. Flowchart of NTF simulator logic.

Appendix B

Input Files

The computer model requires four input files: simulation parameters and constants, schedule of test conditions, schedule of angles of attack, and the proposed test plan. The format of each of these files, referred to as **file1**, **file2**, **file3**, and **file4** in the source code, is defined in this appendix.

File1 Simulation Parameters

This file defines the parameters, constants, input files, and the output files used by the NTF simulation model computer code. The file is divided into two sections. The first section of the file defines the file names containing the input schedules, the file names containing the output data, and the case identification. The second section of the file contains the parameters used in the calculations. The sections consist of a series of input records, each containing two fields. The first field (40 columns of each record) is ignored. The space allows the user to note information about the record, such as the variable name, the input units, or the variable definition. The second field contains the value of the variable being defined. The parameter or variable that is defined on each record depends on the position of the record in the file. File names in the first section are entered between columns 41 and 70 and are left justified. Parameter values in the second section are input between columns 41 and 50 and must contain a decimal point. The parameters are defined in order of input in table B1. A sample input file is found in appendix C.

Table B1. Simulation Parameters File Variable Definitions

Variable	Unit	Baseline value	Definition
file2		____.tc	Input file name containing test conditions.
file3		____.aoa	Input file name containing angle-of-attack schedules.
file4		____.input	Input file name containing proposed test plan.
file9		____.dat	Output file name containing detailed output from simulator code.
file8		____.ffsif	Output file name of ASCII free format standard interface file suitable for plotting history of consumables.
caseid			Case identification to be placed first in output file.
newsup	ton	2652	Initial level in manufacturer's off-site LN_2 supply tank (1).
newsto	ton		Initial level in optional LN_2 storage tank (3).
newops	ton	848	Initial level in NTF on-site LN_2 operations tank (2).
elnew	kWh	0	Initial electrical consumption.
airnew	lbm	0	Initial high-pressure air consumption.
ln2new	ton	0	Initial LN_2 consumption.
tdata	sec	26.4	Average sec required to take a data point. NOTE: Set **tdata**=0 to specify detailed parameters for data acquisition process.
tstart	hr		Start time of first shift. (Typically 8.0 hr for two-shift operations and 0.0 hr for three-shift operations.)
tbegin	hr		Beginning time for first process, relative to midnight between Sunday night and Monday morning (e.g., 8:00 a.m. on Tuesday would be 32.0 hr).
daylen	hr		Length of workday. (Typically 14.5 hr for two-shift operations and 21.5 hr for three-shift operations.)
wkleng	day	5	Length of work week (5 or 7 days only).
tacc	hr	0.75	Time required to gain access to model after drive fan has stopped and tunnel has reached stagnant conditions.
balcon	hr		Time spent conditioning balance after test gas reaches specified temperature. Typical values are 1.0 hr for thin-wall models like fighters and high-speed civil transports and 1.5 hr for thick-wall models such as shuttle or subsonic transports.
tmcrate	°F/hr	150	Rate at which model is warmed (conditioned) before starting model change.
tonoff	hr	0.5	Time required to obtain a wind-off zero. Included is time to bring tunnel to stagnant conditions after completing balance-conditioning process, record wind-off zero, obtain a full ESP calibration, and bring test conditions back to those specified for first run.

Table B1. Continued

Variable	Unit	Baseline value	Definition
tsup	hr	0.5	Time required to start tunnel systems before starting a tunnel run.
tdry	hr	4.0	Time required to drain and dry cooling coils.
ptstart	psi		Initial total presure in tunnel circuit before first process.
tmpnew	°F		Initial total temperature in tunnel circuit before first process.
ops		0	Initial tunnel operations mode: ops=0 for air operations. ops=1 for GN_2 operations.
tt1	°F	100.0	Threshold temperature for air operations. If stagnation temperature specified in test conditions is equal to or greater than **tt1**, the polar will be run in air mode; otherwise, it will be run in GN_2 mode.
tgn2	hr	1.5	Time required to complete an exchange of test gas from air to GN_2.
volln2	ton/hr	59.5	LN_2 use rate when exchanging test gas from air to GN_2.
volpow	MW	12.0	Fan power used during gas volume exchange.
accair	lbm/min	2.0	High-pressure air rate to maintain positive differential pressure in access housings when tunnel circuit contains GN_2.
voltmp	°F	100.0	Temperature of test gas at completion of test gas exchange.
tt3	°F	–40.0	Dew point conditioning threshold temperature.
tt4	°F	–50.0	Dew point conditioning threshold temperature.
tdew	hr	1.0	Time to complete dew point process.
dewln2	ton	150.0	LN_2 required to complete dew point process.
dewpow	MW	10.0	Fan power used during dew point process.
dewtmp	°F	100.0	Test circuit gas temperature at end of dew point process.
deltmp	°F	50.0	Maximum temperature change between test conditions that does not require warm-up/cooldown procedure.
clrtmax	°F/hr	72.0	Maximum gas cooldown rate at upper temperature (T_u). (See fig. 11.)
clrtmin	°F/hr	36.0	Gas cooldown rate at lower temperature (T_l). (See fig. 11.)
cllnmax	gal/min	400.0	Maximum LN_2 flow rate for cooldown process (at $T \leq T_m$). (See fig. 11.)
cllnmin	gal/min	200.0	Minimum LN_2 flow rate for cooldown process (at upper temperature, T_u). (See fig. 11.)
clstar	°F	–200.0	Temperature (T_m) at which maximum cooldown rate cannot be sustained. (See fig. 11.)
coolfp	MW	1.5	Fan power used during cooldown process.
wrmrat	°F/hr	72.0	Gas warm-up rate.
wrmpow	MW	7.0	Fan power used during warm-up process.
airtmp	°F	100.0	Temperature of GN_2 at end of warm-up required before changing gas from GN_2 to air.
tair	hr		Time required to complete gas exchange from GN_2 to air.
airpow	MW	7.0	Fan power used during gas exchange from GN_2 to air.
deltap	psi	40.0	Change in pressure in each cycle to exchange test gas from GN_2 to air.
cycles		5	Number of cycles required to exchange test gas from GN_2 to air.
prate	psi/hr	60.0	Tunnel pressurization rate in air mode.
amass	lbm/psi	1200.0	Amount of air required to increase circuit pressure 1 psi.
airrun	lbm/hr	0	High-pressure air use rate during an air run. (For future use.)
ratedel	ton/hr	45.0	Delivery rate of LN_2 from manufacturer's off-site supply tank to NTF on-site tank or optional storage tank. (See fig. 12.)
ratetra	ton/hr	260.0	Transfer rate of LN_2 from optional storage tank to NTF on-site operations tank. (See fig. 12.)
ratepro	ton/hr	12.5	Production rate of LN_2 at manufacturer's plant. (See fig. 12.)
capsup	ton	2679.0	Capacity of manufacturer's off-site supply tank. (See fig. 12.)
capsto	ton		Capacity of optional storage tank. (See fig. 12.)

Table B1. Concluded

Variable	Unit	Baseline value	Definition
capops	ton	893.0	Capacity of NTF on-site operations tank. (See fig. 12.)
llimsup	ton	28.0	Lower limit of manufacturer's off-site supply tank.
llimsto	ton		Lower limit of optional storage tank.
llimops	ton	89.0	Lower limit of NTF on-site operations tank. Normal value is 10 percent of tank capacity.
ulimsup	ton	2652.0	Upper limit of manufacturer's off-site supply tank.
ulimsto	ton		Upper limit of optional storage tank.
ulimops	ton	848.0	Upper limit of NTF on-site operations tank. Normal value is 95 percent of tank capacity.
pln2	$/ton		Price of LN_2.
pelec	$/kWh		Price of electricity.
pair	$/lbm		Price of high-pressure air.
pfacil	$/hr		Price of facility occupancy per hour.
dphidt	deg/sec	1.5	Roll drive average roll rate.
dthetadt	deg/sec	0.5	Arc sector average pitch rate.
tsetlphi	sec	1.0	Time for roll drive reading to settle.
tsetlalpha	sec	2.0	Time for angle-of-attack reading to settle.
tsetlmach	sec	4.0	Time for test conditions to settle.
tsetltube	sec	4.0	Time for transients to settle before acquiring data.
tacquis	sec	1.0	Time to acquire data.
tzcalib	sec	90.0	Time to complete ESP zero calibration.
ttestcon	sec	180.0	Average time to change test conditions.

File2 Wind Tunnel Test Conditions Schedule

This two-section file defines the wind tunnel test conditions that are required for the proposed test plan. The first section is typically used to provide information about the case and to indicate the variable in each column. These nine header records must be present, but the contents are ignored by the simulator program. The second section contains a series of test conditions and the associated fan power and LN_2 consumption. The second section consists of pairs of input records; the first contains eight variables and the second one is blank. A free-format input is used; that is, the eight variable values are separated by either a blank or a comma. The variables are defined in the order in which they appear in table B2. Reading of the second section of the file is terminated when an end-of-file mark is read. Note that the maximum number of test conditions that can be specified is determined by the value of **imax** in the program source file *ntfsim.param*. A sample input file may be found in appendix C.

Table B2. Test Conditions File Variable Definitions

Variable	Unit	Definition
index		Index used to identify this set of test conditions.
mach		Free-stream Mach number.
pt	psi	Free-stream stagnation pressure.
ttemp	°F	Free-stream stagnation temperature.
rc		Reynolds number based on free-stream conditions and model chord, in millions.
q	psf	Free-stream dynamic pressure.
qoe		Ratio of free-stream dynamic pressure to modulus of elasticity of model material (not used in calculations).
fpow	MW	Fan power.
gpm	gal/min	LN_2 flow rate.

File3 Angles-of-Attack Schedule

This file defines the angle-of-attack schedules that are associated with a particular wind tunnel test condition to complete the specification of the test conditions. The file is divided into two sections. The first section is typically used to define the variable in each column. These two records must be present but the contents are ignored by the simulation program. The second section contains a series of angle-of-attack schedules. The maximum number of schedules that can be specified is determined by the value of **jmax** in the program source file *ntfsim.param*. Each schedule has two parts. A free-format input is used for each part; that is, the variable values are separated by either a blank or a comma. Each part can contain more than one record. The first part defines the schedule index, the model roll angle, and the number of angles of attack in the schedule. The second part contains the angles of attack in the order that they are to be set. Reading of the second section of the file is terminated by an end-of-file mark. The maximum number of angles that can be specified in a schedule is determined by the value of **mmax** in the program source file *ntfsim.param*. Definition of the variables used in the angle-of-attack schedules is defined in table B3. A sample input file may be found in appendix C. In this sample case for **file3**, there are four angle-of-attack schedules, identified as 1, 2, 3, and 5. The fourth schedule, which happens to have an identifying index of 5, will be conducted with the model inverted (phi = 180°), contains 10 angles from 10° to −8° in −2° increments. Since a free-field format input is used, text can be inserted after the last field has been read. In this case, text is used to identify the schedule and the model-roll attitude.

Table B3. Angle-of-Attack Schedule Variable Definitions

Variable	Unit	Definition
index		Identifying index for angle-of-attack schedule
phi	deg	Model roll angle for schedule =0 for upright model =180 for inverted model
aoasch		Number of angles of attack for schedule
aoalist (1 to aoasch)	deg	List of angles to be set for schedule (in order)

File4 Test Plan Sequence

This file defines the test plan sequence to be processed by the NTF simulation program. The file is divided into two sections. The first section is typically used to identify the case. The two records in this section must be present but the contents are ignored by the simulation program. The second section contains a series of commanded processes. The maximum number of processes that can be specified is determined by the value of **kmax** in the program source file *ntfsim.param*. Each process is specified by a single, fixed-format record containing three variables: a process identification number (**itask**), a single process parameter (**ltask**), and task identification text (**taskid**). Since text information is read by the program, a fixed format read is used. The process identification number is a right-justified integer in columns 1 and 2. The process parameter is a right-justified integer in columns 3 to 6. The text identification appears in columns 7 to 36. Reading of the process specifications is terminated by an end-of-file mark. The variables are defined in table B4.

Table B4. Test Plan File Variable Definitions

Variable	Definition
itask	Process (task) specification number— 1 = Tunnel run 2 = Model change 3 = Model installation 4 = Model removal 5 = Tunnel downtime 6 = Tunnel downtime with air mode option 7 = Holiday downtime 99 = End of simulation
ltask	Process parameter— If **itask** = 1, **ltask** = number of polars in run **itask** = 2–6, **ltask** = process elapsed time (in hr) **itask** = 7, **ltask** = process elapsed time (in days) **itask** = 99, **ltask** is not used
taskid	Text to identify task

Tunnel run processes (**itask=1**) require additional inputs to define the test conditions to be set during the tunnel run. These additional inputs are defined on one or more free-format records. Each test condition is defined by a code with the digits left of the decimal point being used to specify the index of the entry in the tunnel test conditions schedule and the two digits to the right of the decimal point being used to specify the index of the entry in the angle-of-attack schedule. The maximum number of polars that can be specified for a run is set by the parameter **lmax** which is defined in the source file *ntfsim.param*. The last line in the file should have **itask=99** to end the simulation program processing.

A sample input file may be found in appendix C. For this sample case, the first process specified is a tunnel run (**itask=1**) with 9 polars (**ltask=9**). The text to identify this task in the output data file is *Run Series #1*. Since the task is a tunnel run, an additional record is required to define the tunnel and model test conditions for each of the nine polars. The first polar has a code of 7.01; therefore, the tunnel test conditions file index is seven and the angle-of-attack file index is one. Using the sample test conditions file and angle-of-attack schedule file in appendix C, the Mach number of this polar is 0.3, and the Reynolds number is 21.5×10^6. The model is upright and has 30 angles of attack ranging from $-6°$ to $16°$.

Appendix C

Sample Input Files

Simulation Parameter File (file1)

```
file2 test condition input file          :test1.tc
file3 AOA schedule input file            :test1.aoa
file4 run sequence input file            :test1.input
file9 data output file                   :test1.dat
file8 plot ffsif output file             :test1.ffsif
caseid case identification               :HSCT test case
newsup (tons)  Supply tank level         =    2652.0
newsto (tons)  Storage tank level        =       0.0
newops (tons)  Ntf tank level            =     848.0
elnew  (kW-hrs)                          =       0.0
airnew (lbm)                             =       0.0
ln2new (tons)                            =       0.0
tdata  (sec/point)                       =      26.4
tstart (hrs.,i.e. 8.0 is 8 a.m.)         =       8.0
tbegin (hrs.)                            =      62.0
daylen (hrs.)                            =      14.5
wkleng (days)                            =       5.0
balcon (hrs.)                            =       1.0
tmcrate (deg/hr)                         =     150.0
tonoff (hrs.)                            =       0.5
tsup   (hrs.)                            =       0.5
tdry   (hrs.)                            =       4.0
ptstart (psia)                           =      14.7
tmpnew (deg F)                           =      70.0
ops (0=air ops, 1=gn2 ops)               =       0
tt1 (deg F)                              =     100.0
tgn2 (hrs.)                              =       1.5
volln2 (tons/hour)  0.10*893.0/1.5       =      59.5
volpow (MW)                              =      12.0
accair (lbm/min)                         =       2.0
voltmp (deg F)                           =     100.0
tt3 (deg F)                              =     -40.0
tt4 (deg F)                              =     -50.0
tdew (hrs.)                              =       1.0
dewln2 (tons)                            =     150.0
dewpow (MW)                              =      10.0
dewtmp (deg F)                           =     100.0
deltmp (deg F)                           =      50.0
clrtmax (deg F/hr.)                      =      72.0
clrtmin (deg F/hr.)                      =      36.0
cllnmax (gpm)                            =     400.0
cllnmin (gpm)                            =     200.0
clstar (deg)                             =    -200.0
coolfp (MW)                              =       1.5
wrmrat (deg F/hr.)                       =      72.0
wrmpow (MW)                              =       7.0
airtmp (deg F)                           =     100.0
tair (hrs.)                              =       1.5
airpow (MW)                              =       7.0
```

```
deltap (psia)                              =      40.0
cycles (# of pressure cycles)              =       5.0
prate (psia/hr)                            =      60.0
amass (lbm air/psia of tunnel pressure)=    1200.0
airrun (lbm/hr.)                           =       0.0
ratedel(tons/hr.)                          =      50.0
ratetra(tons/hr.)                          =     260.0
ratepro(tons/hr.)                          =      12.5
capntf (tons)                              =     893.0
capsto (tons)                              =       0.0
capsup (tons)                              =    2679.0
llimsup (tons)                             =      27.0
llimsto (tons)                             =       0.0
llimops (tons)                             =      89.0
ulimsup (tons)                             =    2652.0
ulimsto (tons)                             =       0.0
ulimops (tons)                             =     848.0
price of LN2 ($/ton)                       =
price of ELECT. ($/kW-hr)                  =
price of air ($/lbm)                       =
price of facility (k$/week)                =
dphidt                                     =       1.5
dthetadt                                   =       0.5
dsetlphi                                   =       1.0
tsetlalpha                                 =       2.0
tsetlmach                                  =       4.0
tsetltube                                  =       4.0
tacquis                                    =       1.0
tzcalib                                    =      90.0
tchtcon                                    =     180.0
```

Test Conditions File (file2)

```
1         PROGRAM NTF-TESTPLAN
2         TUNNEL CONDITIONS BASED ON BB EQ. OF STATE
3
4
5
6 C#     MACH       PT        TT        RC         Q        Q/E        FPWR     LN2
7                   PSIA       F      /10^6      PSF      *10^6       MW       GPM
8
9
  1      .30      18.0      120        4.1       153       .041        2.4        0.

  2      .60      18.8      120        7.7       535       .143       11.2        0.

 65      .80      21.2      120       10.3       897       .239       22.9        0.

  3      .90      20.0      120       10.2       965       .257       25.7        0.

 66      .92      20.0      120       10.3       987       .263       26.4        0.

  4      .95      20.0      120       10.4      1018       .271       27.5        0.

  5      .98      20.0      120       10.5      1047       .279       28.6        0.
```

7	.30	93.8	120	21.5	803	.214	12.4	0.
8	.60	60.7	43	30.0	1731	.457	34.3	1639.
12	.30	95.3	-4	29.9	817	.214	11.4	582.
15	.90	36.3	-52	30.0	1754	.457	39.7	2184.
63	.95	34.5	-61	30.0	1757	.457	39.9	2226.
64	.98	33.5	-66	30.0	1754	.456	40.0	2253.
17	.98	20.6	-88	20.0	1078	.280	23.9	1393.
18	.30	96.4	-90	40.0	826	.214	10.3	611.
19	.95	20.6	-91	20.0	1048	.272	22.9	1343.
21	.90	20.6	-97	20.0	994	.258	21.3	1259.
59	.60	62.0	-111	50.1	1768	.457	29.1	1775.
23	.30	31.0	-118	14.4	264	.068	3.2	197.
25	.30	97.2	-143	49.8	832	.214	9.7	632.
26	.30	18.7	-151	10.0	159	.041	1.8	120.
29	.60	29.3	-164	29.9	834	.214	12.7	855.
33	.98	20.8	-178	29.9	1088	.279	21.0	1454.
34	.60	19.6	-179	21.6	557	.143	8.3	573.
36	.95	20.8	-180	29.9	1058	.271	20.1	1401.
38	.90	20.8	-184	29.9	1004	.257	18.7	1313.
42	.30	31.3	-201	21.5	266	.068	2.8	205.
60	.60	62.9	-207	80.2	1789	.457	24.8	1855.
43	.30	18.8	-219	14.3	160	.041	1.6	123.
45	.30	98.9	-230	80.0	841	.214	8.5	678.
62	.90	37.2	-231	70.1	1793	.457	30.2	2372.
46	.60	19.7	-235	29.9	560	.143	7.4	585.
50	.30	99.4	-247	90.0	843	.214	8.3	692.
51	.90	37.3	-249	79.4	1797	.457	29.0	2386.
53	.30	31.6	-252	29.8	268	.068	2.5	211.

```
 56      .95      35.4     -254       79.9      1798       .457       29.0       2420.

 61      .60      63.5     -255      110.2      1798       .457       22.3       1886.

 57      .98      34.5     -256       79.9      1802       .457       29.2       2442.

 70      .30      18.0       90        4.1       153       .041        2.4       0.
```

Angles-of-Attack Schedule File (file3)

```
Sch   roll   npts   notes  (Angle schedule - test case)
pitch angles
1      0.0   30      Schedule 1 (upright)
-6.0 -5.5 -5.0 -4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5
-1.0 -0.5  0.0  0.5  1.0  2.0  3.0  4.0  5.0  6.0
 7.0  8.0  9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0
2      0.0   20      Schedule 2 (upright)
 0.0   -6.0 -5.5 -5.0 -4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5
-1.0 -0.5  0.0  0.5  1.0  2.0  3.0  4.0  5.0  6.0
3      0.0   15      Schedule 3 (upright)
-6.0 -5.0 -4.0 -3.0 -2.0 -1.0  0.0  1.0  2.0  4.0
 6.0  8.0 10.0 12.0 14.0
5    180.0   10      Schedule 5 (inverted)
10.0  8.0  6.0  4.0  2.0  0.0 -2.0 -4.0 -6.0 -8.0
```

Test Plan Schedule File (file4)

```
(Test Plan - test case)
Task Time  Text
 1   9     Run Series #1
 7.01 1.01 1.04 2.01 2.04 3.04 1.01 65.01 3.01
 1  14     Run Series #2
 3.04 1.04 1.01 3.01 66.01 4.01 5.01 3.01 1.01 3.01 1.01 3.01 1.01 3.01
 1   1     Run Series #3
51.01
 1  12     Run Series #4
51.01 53.01 51.04 61.04 61.01 50.01 50.04 50.01 51.01 56.01 53.01 57.01
 1  13     Run Series #5a
51.01 53.01 51.01 51.04 51.01 50.01 50.04 50.01 50.01 50.01 50.01 51.01 51.01
 1   1     Run Series #5b
53.01
 1  10     Run Series #6
62.01 45.01 45.04 46.01 43.01 29.01 29.04 26.04 26.01 25.01
 1  12     Run Series #7a
60.01 42.01 42.04 38.04 38.01 33.01 36.01 34.01 38.01 38.01 38.01 38.01
 1  12     Run Series #7b
23.04 23.01 21.04 21.01 21.01 19.01 21.01 17.01 21.01 21.01 18.04 18.01
 1   6     Run Series #8
12.04 12.01 12.01 12.01 12.01 12.01
 1   4     Run Series #9a
15.04 15.01 15.01 15.01
 1   4     Run series 9b
15.01 15.01 63.01 64.01
 2   6     * Change to High-Lift Config *
 1  12     Run Series #10
23.04 23.01 18.01 12.04 12.01 12.01 12.01 12.01 12.01 12.01 12.01 12.01
```

```
 1  14     Run Series #11
 1.04 1.01 1.01 1.01 1.01 1.01 1.01 7.04 7.01 7.01 7.01 7.01 7.01 7.01
 5  98     Holiday Down-Time (7 days)
 1   2     Run Series #12
25.04 25.01
 1   8     Run Series #13a
53.01 53.04 53.01 53.01 53.01 53.01 53.01 53.01
 1   4     Run Series #13b
50.04 50.01 50.01 50.01
 6  51     Hardware failure (4 days)
 1   8     Run Series #14
50.04 50.01 50.01 45.04 45.01 43.01 42.04 42.01
 2   8     * Change to Transonic Config *
 1  10     Run Series #15
51.04 51.01 51.01 51.01 51.01 51.01 51.01 57.01 56.01 56.01
 1   9     Run Series #16
38.04 38.01 38.01 38.01 38.01 38.01 38.01 36.01 33.01
99
```

Appendix D

Output File Description

The simulation computer program generates two output files: a detailed listing of the case and a plot file. This appendix describes the format and contents of these two files. The name of the file containing the detailed listing is specified by the parameter **file9**, and the name of the plot file is specified by the parameter **file8** in the simulation parameters file, **file1**.

Detailed Listing File

The detailed listing file contains a summary of the input files, the time history of several variables as the test plan was processed, and a summary of the process. The date and time that the case was run, the version of the simulation computer code, and the case identification are listed at the top of the input files summary. The values of the more frequently changed parameters in **file1** are listed. The inputs from the wind tunnel test conditions file and the angle-of-attack schedules file follow. The parameters listed in the detailed listing file for the wind tunnel test conditions file are described in table B2, and the parameters listed for the angle-of-attack schedule are described in table B3.

The time history of the file begins with text that defines the column headings and the units. The first two columns are the day and time at the end of the process. The last eight columns are the process variables that are tracked. The variable definitions are presented in table D1. At the completion of each process the value of each variable is listed, followed by a text description of the process and a blank line. In some cases, a process cannot be completed on the day that it started. Advisory messages are included in the listing whenever process completion does not occur. In addition, if there are any problems with the LN_2 tank levels, warning messages are written to the file. The warning messages do not require any action by the user; they serve only to alert the user to potential problems when the test plan is actually being conducted at the NTF.

Table D1. Definition of Parameters in Detailed Listing and Plot Files

Column heading	Unit	Definition
day	day	Number of days
time	hr	Elapsed time
ln2	ton	Cumulative LN_2 consumption
ttemp	°F	Tunnel stagnation temperature
ntf	ton	LN_2 remaining in NTF operations tank (2)
sto	ton	LN_2 remaining in optional storage tank (3)
supply	ton	LN_2 remaining in manufacturer's off-site supply tank (1)
total	ton	Total LN_2 remaining in tanks used in simulation
electr	kWh	Cumulative electrical consumption
air	lbm	Cumulative high-pressure air consumption

The summary of results from processing the test plan follows the detailed time history. The *LN2 summary* lists the totals for the LN_2 supply system. The losses are the heat losses in the NTF operations tank and the optional storage tank and the piping losses that occur in delivery from the manufacturer's supply tank and transfer from the optional storage tank. The *time summary* is the total number of hours that the NTF was staffed for operations and the test had access to the test section. The fan-on hours summary indicates the time that the fan was running. The lost time is the total of the times that operations were terminated because the process could not be completed before the end of the workday, the total times that there was insufficient LN_2 in the NTF operations tank to complete a process or polar, and the total times that a cooldown had to be delayed. All times that the manufacturer could not produce LN_2 because the off-site supply tank was at the upper limit (including times that the NTF is not staffed to run, such as weekends) are summed and the result follows the time summary. The *operations cost* lists the cost for each consumable and the total cost to complete the test plan. The *process breakdown* lists the number of occurrences and the total time spent on each process listed. If

the detailed description of the data acquisition process is used (**tdata**=0), the times for the associated subprocesses are tracked and the total appears for the data acquisition time. Individual occurrences are not tracked for these subprocesses. The total number of GN_2 (cryo) and air data points and polars are listed. The minimum levels in each LN_2 tank that occurred during test plan processing are at the end of the listing. Part of a sample detailed listing file is found in appendix E.

Plot File

The plot file contains a history of the same parameters listed in the detailed listing file that was just described. However, the value for the day is the number of days (including fractions of a day) relative to midnight, the beginning of Monday morning of the first week of the test. The file format is compatible with different spreadsheet programs available on personal computers. The file consists of a single names record, followed by multiple pairs of records that define the variable values. There are 10 variables in the plot file. The variable names and definitions are presented in table D1. The order of the data in each data record is the same as the order of the names in the names record. A data record requires two lines and is written in a 6F13.6 format. The contents of these records are the same as those found in the detailed listing file.

Appendix E

Sample Output File (file9)

```
1                        NTF Process Simulator        Mon Jul 11 10:27:15 1994
                             Version:  1.0


                     test case 1 (HSCT Test 60)

     Simulator parameters   file: test1.start

 Initial conditions:

            LN2 tank level                              Tunnel gas
       operations (NTF) 2    848. tons            Pressure        15. psi
         storage  (NTF) 3      0. tons            Temperature     70. deg
         supply (manf.) 1   2652. tons            Air operations


 Workweek:  5. days,   14.5 hours long,  day starts at  8.0,  test begins at  62.0
hours

 Cooldown:       rate    72.0 (max)    36.0 (min) deg per hour
                 LN2    400.0 (max)   200.0 (min) gal per min
               tstar  -200.0 deg
          fan power     1.5 megawatts

 Warmup:         rate    72.0 deg per hour
          fan power     7.0 megawatts

                          Capacity  Operational levels (in tons)
 LN2 Tanks:  (2) NTF ops.     893.   (min.  89.   max.  848.)
             (3) NTF sto.       0.   (min.   0.   max.    0.)
             (1) manf.       2679.   (min.  27.   max. 2652.)

 LN2 delivery rate      45.0 tons per hour
     production rate    12.5 tons per hour
     transfer rate       0.0 tons per hour

 Systems start-up delay      0.5 hours
 Dew point conditioning      1.0 hours
 Balance conditioning        1.0 hours
 Model conditioning rate   150.0 deg/hour
 Wind off                    0.5 hours
 Cooling coil drying         4.0 hours

 Ave. data rate             26.4 seconds per point
```

1 Test Conditions

file :test1.tc

Index	Mach	Pt psi	Tt F	Re million	q psf	fan Megawatt	LN2 gpm
1	0.30	18.0	120.	4.1	153.	2.4	0.
2	0.60	18.8	120.	7.7	535.	11.2	0.
65	0.80	21.2	120.	10.3	897.	22.9	0.
3	0.90	20.0	120.	10.2	965.	25.7	0.
66	0.92	20.0	120.	10.3	987.	26.4	0.
4	0.95	20.0	120.	10.4	1018.	27.5	0.
5	0.98	20.0	120.	10.5	1047.	28.6	0.
7	0.30	93.8	120.	21.5	803.	12.4	0.
8	0.60	60.7	43.	30.0	1731.	34.3	1639.
12	0.30	95.3	-4.	29.9	817.	11.4	582.
15	0.90	36.3	-52.	30.0	1754.	39.7	2184.
63	0.95	34.5	-61.	30.0	1757.	39.9	2226.
64	0.98	33.5	-66.	30.0	1754.	40.0	2253.
17	0.98	20.6	-88.	20.0	1078.	23.9	1393.
18	0.30	96.4	-90.	40.0	826.	10.3	611.
19	0.95	20.6	-91.	20.0	1048.	22.9	1343.
21	0.90	20.6	-97.	20.0	994.	21.3	1259.
59	0.60	62.0	-111.	50.1	1768.	29.1	1775.
23	0.30	31.0	-118.	14.4	264.	3.2	197.
25	0.30	97.2	-143.	49.8	832.	9.7	632.
26	0.30	18.7	-151.	10.0	159.	1.8	120.
29	0.60	29.3	-164.	29.9	834.	12.7	855.
33	0.98	20.8	-178.	29.9	1088.	21.0	1454.
34	0.60	19.6	-179.	21.6	557.	8.3	573.
36	0.95	20.8	-180.	29.9	1058.	20.1	1401.
38	0.90	20.8	-184.	29.9	1004.	18.7	1313.
42	0.30	31.3	-201.	21.5	266.	2.8	205.
60	0.60	62.9	-207.	80.2	1789.	24.8	1855.
43	0.30	18.8	-219.	14.3	160.	1.6	123.
45	0.30	98.9	-230.	80.0	841.	8.5	678.
62	0.90	37.2	-231.	70.1	1793.	30.2	2372.
46	0.60	19.7	-235.	29.9	560.	7.4	585.
50	0.30	99.4	-247.	90.0	843.	8.3	692.
51	0.90	37.3	-249.	79.4	1797.	29.0	2386.
53	0.30	31.6	-252.	29.8	268.	2.5	211.
56	0.95	35.4	-254.	79.9	1798.	29.0	2420.
61	0.60	63.5	-255.	110.2	1798.	22.3	1886.
57	0.98	34.5	-256.	79.9	1802.	29.2	2442.
70	0.30	18.0	90.	4.1	153.	2.4	0.

1 Angle of Attack Schedules

file: test1.aoa

Index	Phi	npt	alpha=									
1	0.0	30	-9.0	-8.0	-7.0	-6.0	-5.0	-4.0	-3.0	-2.0	-1.0	-0.5
			0.0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6
			4.0	5.0	7.0	9.0	11.0	12.0	13.0	14.0	15.0	16.0
2	0.0	25	-9.0	-8.0	-7.0	-6.0	-5.6	-5.2	-4.8	-4.4	-4.0	-3.6
			-3.2	-2.8	-2.4	-2.0	-1.6	-1.2	-0.8	-0.4	0.0	0.4
			0.8	1.2	1.6	1.0	3.0					
3	0.0	15	-6.0	-5.0	-4.0	-3.0	-2.0	-1.0	0.0	1.0	2.0	4.0
			6.0	8.0	10.0	12.0	14.0					
5	180.0	7	8.0	7.0	6.0	5.0	4.0	3.0	2.0			

1

day	time (hr)	ln2 (tons)	ttemp (degF)	ntf (tons)	sto (tons)	supply (tons)	total (tons)	electr (kW-hr)	air (lbm)	
3	62.00	0.0	70.0	848.0	0.0	2652.0	3500.0	0.	0.	
Initial conditions										
3	62.50	0.0	70.0	848.0	0.0	2651.9	3499.8	0.	0.	
Delay for start-up tasks, 0.50 hours										
3	63.82	0.0	120.0	847.8	0.0	2651.5	3499.3	0.	94920.	
Tunnel pressurized for start of air runs										
3	64.32	0.0	120.0	847.8	0.0	2651.4	3499.1	3500.	94920.	
Wind off zero acquired										
3	64.54	0.0	120.0	847.8	0.0	2651.3	3499.1	6228.	94920.	
Run Series #1 and #2 in air mode Mach= 0.30 Rc= 21.5 mil. (air) 30 points										
3	64.76	0.0	120.0	847.7	0.0	2651.2	3499.0	6756.	94920.	
Run Series #1 and #2 in air mode Mach= 0.30 Rc= 4.1 mil. (air) 30 points										
3	64.81	0.0	120.0	847.7	0.0	2651.2	3499.0	6879.	94920.	
Run Series #1 and #2 in air mode Mach= 0.30 Rc= 4.1 mil. (air) 7 points										
3	65.03	0.0	120.0	847.7	0.0	2651.2	3498.9	9343.	94920.	
Run Series #1 and #2 in air mode Mach= 0.60 Rc= 7.7 mil. (air) 30 points										
3	65.08	0.0	120.0	847.7	0.0	2651.1	3498.9	9918.	94920.	
Run Series #1 and #2 in air mode Mach= 0.60 Rc= 7.7 mil. (air) 7 points										
3	65.13	0.0	120.0	847.7	0.0	2651.1	3498.8	11237.	94920.	
Run Series #1 and #2 in air mode Mach= 0.90 Rc= 10.2 mil. (air) 7 points										
3	65.35	0.0	120.0	847.7	0.0	2651.1	3498.8	11765.	94920.	
Run Series #1 and #2 in air mode Mach= 0.30 Rc= 4.1 mil. (air) 30 points										
3	65.57	0.0	120.0	847.7	0.0	2651.0	3498.7	16803.	94920.	
Run Series #1 and #2 in air mode Mach= 0.80 Rc= 10.3 mil. (air) 30 points										
3	65.76	0.0	120.0	847.7	0.0	2651.0	3498.6	21515.	94920.	
Run Series #1 and #2 in air mode Mach= 0.90 Rc= 10.2 mil. (air) 25 points										
3	65.81	0.0	120.0	847.6	0.0	2650.9	3498.6	22834.	94920.	
Run Series #1 and #2 in air mode Mach= 0.90 Rc= 10.2 mil. (air) 7 points										
3	65.86	0.0	120.0	847.6	0.0	2650.9	3498.6	22958.	94920.	
Run Series #1 and #2 in air mode Mach= 0.30 Rc= 4.1 mil. (air) 7 points										
3	66.08	0.0	120.0	847.6	0.0	2650.9	3498.5	23486.	94920.	
Run Series #1 and #2 in air mode Mach= 0.30 Rc= 4.1 mil. (air) 30 points										
3	66.26	0.0	120.0	847.6	0.0	2650.8	3498.4	28197.	94920.	
Run Series #1 and #2 in air mode Mach= 0.90 Rc= 10.2 mil. (air) 25 points										
3	66.48	0.0	120.0	847.6	0.0	2650.7	3498.3	34005.	94920.	
Run Series #1 and #2 in air mode Mach= 0.92 Rc= 10.3 mil. (air) 30 points										

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3   66.66     0.0  120.0   847.6     0.0  2650.7  3498.3    39047.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.95   Rc= 10.4 mil. (air)   25 points

3   66.85     0.0  120.0   847.5     0.0  2650.6  3498.2    44290.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.98   Rc= 10.5 mil. (air)   25 points

3   67.07     0.0  120.0   847.5     0.0  2650.6  3498.1    49944.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.90   Rc= 10.2 mil. (air)   30 points

3   67.29     0.0  120.0   847.5     0.0  2650.5  3498.0    50472.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.30   Rc=  4.1 mil. (air)   30 points

3   67.47     0.0  120.0   847.5     0.0  2650.5  3498.0    55184.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.90   Rc= 10.2 mil. (air)   25 points

3   67.69     0.0  120.0   847.5     0.0  2650.4  3497.9    55712.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.30   Rc=  4.1 mil. (air)   30 points

3   67.88     0.0  120.0   847.5     0.0  2650.4  3497.8    60424.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.90   Rc= 10.2 mil. (air)   25 points

3   68.10     0.0  120.0   847.4     0.0  2650.3  3497.7    60952.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.30   Rc=  4.1 mil. (air)   30 points

3   68.28     0.0  120.0   847.4     0.0  2650.2  3497.7    65663.    94920.
     Run Series #1 and #2 in air mode   Mach= 0.90   Rc= 10.2 mil. (air)   25 points

3   68.78     0.0  120.0   847.4     0.0  2650.1  3497.5    65663.    94920.
Delay for start-up tasks,  0.50 hours

Not enough time on shift,   lost time=    1.72

4   80.00     0.0  120.0   846.3     0.0  2647.0  3493.3    65663.    94920.
Conditions after either lost time or at start of next shift

4   84.00     0.0  120.0   846.0     0.0  2649.9  3495.8    65663.    94920.
Cooing coil drying is complete

4   85.50    89.2  100.0   823.6     0.0  2588.2  3411.8    83663.    95100.
Volume exchange to GN2 is complete

4   92.10   514.7 -249.0   692.4     0.0  2371.8  3064.2    93566.    95892.
Cooldown, balance conditioning, and wind-off zero for next condition is complete

4   92.29   603.2 -249.0   612.0     0.0  2365.8  2977.8    98883.    95914.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)   25 points

4   92.47   691.8 -249.0   531.6     0.0  2359.8  2891.4   104199.    95936.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)   25 points

4   92.69   701.2 -252.0   532.0     0.0  2352.6  2884.6   104749.    95963.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 29.8 mil. (GN2)   30 points

4   92.74   726.0 -249.0   509.5     0.0  2350.9  2860.4   106238.    95969.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)    7 points

4   92.79   745.6 -255.0   492.2     0.0  2349.2  2841.4   107383.    95975.
     Run Series #3 to #5b in Cryo mode  Mach= 0.60   Rc=110.2 mil. (GN2)    7 points
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4   93.01   829.6 -255.0   418.0     0.0  2342.0  2760.0   112289.    96001.
     Run Series #3 to #5b in Cryo mode  Mach= 0.60   Rc=110.2 mil. (GN2)   30 points

4   93.23   860.4 -247.0   397.0     0.0  2334.8  2731.8   114115.    96028.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)   30 points

4   93.28   867.6 -247.0   392.1     0.0  2333.1  2725.2   114541.    96034.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)    7 points

4   93.50   898.4 -247.0   371.1     0.0  2325.9  2697.0   116367.    96060.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)   30 points

4   94.50   898.4 -237.9   415.6     0.0  2293.2  2708.8   116367.    96180.
Cooldown delayed,   lost time    1.00 hours

5  104.00   898.4 -171.3   839.0     0.0  1981.8  2820.8   116367.    96240.
Conditions after either lost time or at start of next shift

5  104.50   898.4 -167.9   846.9     0.0  1979.9  2826.8   116367.    96300.
Delay for start-up tasks,  0.50 hours

5  107.38  1129.7 -249.0   744.0     0.0  1885.5  2629.5   120689.    96646.
Cooldown, balance conditioning, and wind-off zero for next condition is complete

5  107.56  1218.3 -249.0   663.6     0.0  1879.5  2543.1   126005.    96668.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)   25 points

5  107.75  1308.1 -254.0   582.0     0.0  1873.5  2455.5   131322.    96690.
     Run Series #3 to #5b in Cryo mode  Mach= 0.95   Rc= 79.9 mil. (GN2)   25 points

5  107.97  1317.5 -252.0   582.4     0.0  1866.2  2448.7   131872.    96716.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 29.8 mil. (GN2)   30 points

5  108.15  1408.1 -256.0   500.0     0.0  1860.2  2360.2   137225.    96738.
     Run Series #3 to #5b in Cryo mode  Mach= 0.98   Rc= 79.9 mil. (GN2)   25 points

5  108.33  1496.7 -249.0   419.6     0.0  1854.2  2273.8   142542.    96760.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)   25 points

5  108.55  1506.1 -252.0   420.0     0.0  1847.0  2267.0   143092.    96787.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 29.8 mil. (GN2)   30 points

5  108.74  1594.6 -249.0   339.6     0.0  1841.0  2180.6   148409.    96809.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)   25 points

5  108.79  1619.4 -249.0   317.1     0.0  1839.3  2156.4   149897.    96815.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)    7 points

5  108.97  1708.0 -249.0   236.7     0.0  1833.3  2070.0   155214.    96837.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)   25 points

5  109.19  1738.8 -247.0   215.7     0.0  1826.1  2041.8   157040.    96863.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)   30 points

5  109.24  1746.0 -247.0   210.8     0.0  1824.4  2035.2   157466.    96869.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)    7 points
5  109.46  1776.8 -247.0   189.8     0.0  1817.2  2007.0   159292.    96896.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)   30 points
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 5  109.68  1807.6 -247.0   168.8     0.0  1810.0  1978.8   161118.    96922.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)   30 points

 5  109.90  1838.4 -247.0   147.7     0.0  1802.8  1950.5   162944.    96948.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)   30 points

 5  110.12  1869.3 -247.0   126.7     0.0  1795.6  1922.3   164770.    96975.
     Run Series #3 to #5b in Cryo mode  Mach= 0.30   Rc= 90.0 mil. (GN2)   30 points

 Out of LN2 at NTF,   lost time=    8.38

 8  176.00  1869.3  -47.9   846.3     0.0  1869.5  2715.8   164770.    96997.
 Conditions after either lost time or at start of next shift

 8  180.55  2205.1 -249.0   713.2     0.0  1720.4  2433.6   171591.    97543.
 Cooldown, balance conditioning, and wind-off zero for next condition is complete

 8  180.73  2293.7 -249.0   632.8     0.0  1714.4  2347.2   176908.    97565.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)   25 points

 8  180.91  2382.2 -249.0   552.4     0.0  1708.4  2260.8   182224.    97587.
     Run Series #3 to #5b in Cryo mode  Mach= 0.90   Rc= 79.4 mil. (GN2)   25 points


                    (This portion of output deleted to save space)


38  901.98  9070.4 -184.0   398.1     0.0  1653.3  2051.4   754684.   117169.
     Run Series #15 and #16             Mach= 0.90   Rc= 29.9 mil. (GN2)   25 points

38  902.17  9119.2 -184.0   357.6     0.0  1647.3  2004.8   758113.   117191.
     Run Series #15 and #16             Mach= 0.90   Rc= 29.9 mil. (GN2)   25 points

38  902.35  9167.9 -184.0   317.0     0.0  1641.3  1958.3   761541.   117213.
     Run Series #15 and #16             Mach= 0.90   Rc= 29.9 mil. (GN2)   25 points

38  902.53  9216.6 -184.0   276.4     0.0  1635.3  1911.7   764969.   117235.
     Run Series #15 and #16             Mach= 0.90   Rc= 29.9 mil. (GN2)   25 points

38  902.72  9268.6 -180.0   232.6     0.0  1629.2  1861.9   768654.   117257.
     Run Series #15 and #16             Mach= 0.95   Rc= 29.9 mil. (GN2)   25 points

38  902.90  9322.6 -178.0   186.8     0.0  1623.2  1810.1   772504.   117279.
     Run Series #15 and #16             Mach= 0.98   Rc= 29.9 mil. (GN2)   25 points


 Test sequence complete
```

1 Summary

LN2 summary:

Initial storage		3500.	(tons)
Production	+	8663.	
Usage	-	9323.	
Losses	-	358.	
Final storage		1810.	(Calculated 1810.)

Time summary:

Occupancy hours: 363.40 (Includes 58.00 hours down time)
Fan on hours: 113.83
Lost time: 53.41

Lost production time at manufacturers plant: 147.88 hours

Operations Cost:

LN2 costs	= $K	XXXX.	9681.	tons (used and lost)
ELECTRICITY costs	= $K	XX.	772504.	kilowatt-hours
AIR costs	= $K	X.	117279.	lbm
FACILITY costs	= $K	XXXX.	5.01	weeks
TOTAL cost of test	= $K	XXXX.		

Process breakdown	Num.	Time	
Model installation	0	0.00	
Model removal	0	0.00	
Model change	2	12.00	
Plenum access	4	3.00	
Model conditioning	2	2.65	
Start-up delays	14	7.00	
Cooling coil drying	3	12.00	
Gas exchange	5	7.50	
Dew point procedure	4	4.00	
Tunnel cooldown	13	33.00	
Balance conditioning	18	18.00	
Wind off	14	7.00	
Warm tunnel	11	13.89	
Change cryo test cond.		0.00	|
Change air test cond.		0.00	|
Roll model		0.00	|
ESP zero cal.		0.00	|
Pitch model		0.00	|
Test condition settling		0.00	|
Pressure tube settling		0.00	|
Data acquisition		29.07	
Down time	1	58.00	
Holiday time	1	101.50	
Lost 1 (No time)	3	2.83	
2 (No LN2)	4	37.05	
3 (No cooldown)	4	13.53	
Misc	2	1.37	

Total 363.40 hours

Number of:	Polars	Points
Cryo	128	3050
Air	37	914

Minimum LN2 tank levels: operations 101. tons
storage 0. tons
supply 27. tons

Ave. number of points/polar: 24.0
Ave. number of polars/tunnel run: 11.8

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1995	Technical Memorandum

4. TITLE AND SUBTITLE
Computer Model To Simulate Testing at the National Transonic Facility

5. FUNDING NUMBERS
WU 505-59-10-31

6. AUTHOR(S)
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and Judith A. Hannon

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17459

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-4664

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 09
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A computer model has been developed to simulate the processes involved in the operation of the National Transonic Facility (NTF), a large cryogenic wind tunnel at the Langley Research Center. The simulation was verified by comparing the simulated results with previously acquired data from three experimental wind tunnel test programs in the NTF. The comparisons suggest that the computer model simulates reasonably well the processes that determine the liquid nitrogen (LN_2) consumption, electrical consumption, fan-on time, and the test time required to complete a test plan at the NTF. From these limited comparisons, it appears that the results from the simulation model are generally within about 10 percent of the actual NTF test results. The use of actual data acquisition times in the simulation produced better estimates of the LN_2 usage, as expected. Additional comparisons are needed to refine the model constants. The model will typically produce optimistic results since the times and rates included in the model are typically the optimum values. Any deviation from the optimum values will lead to longer times or increased LN_2 and electrical consumption for the proposed test plan. Computer code operating instructions and listings of sample input and output files have been included.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Wind tunnels; Simulation	44
	16. PRICE CODE: A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	